A Review on Research Methods of Disturbance Propagation in Large-Scale Power Grids

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Abstract. Nowadays, our country has entered the era of UHV and large-scale power grid, the scale of power grid is increasing continuously, which has contributed to develop the optimal allocation of resources adequately, meanwhile, the possibilities of the occurrence of large-scale blackouts increased, posing a new challenge for security and stability controlling for power system. Therefore, a growing number of scholars began to focus on the process of disturbance propagation, which can help us gain deeper insight into the performance of power system and offer some valuable suggestion for controlling measurements. Based on the current research status about disturbance propagation, research methods used to reveal the mechanism of disturbance propagation were classified into five types: time-domain simulation methods and their counterparts with transient energy function, linearization analysis, flow analysis algorithms and graph theory analysis methods included. Meanwhile, every existing method was described in detail from four different aspects: concept, present status and hotspots, critical difficulties, future direction. Finally, the future development trend in the field is focused.

1. Introduction

Nowadays, our country has entered the era of UHV and large-scale power grid, the scale of power grid is increasing continuously, which has contributed to develop the optimal allocation of resources adequately, meanwhile, the possibilities of the occurrence of large-scale blackouts increased, which may result in the national grid collapse. This can be proved by the occurrence of major power outages [1-4] in recent years. The primary task to curb the blackout is to understand the process of disturbance propagation in power system. Therefore, it is important to do some researches about disturbance propagation.

From different angles, with different research methods, a deep and extensive research about disturbance propagation in large-scale power grid is carried out by some scholars at home and abroad, some achievements have been obtained. For example, the time-domain simulation method, which is used to analysis the problem about disturbance propagation through the response curves of each variable which are obtained by solving the nonlinear equations. The transient energy function method, which started from the angle of energy, and proposed that the disturbance is spread in the power grid
in the form of energy, linearization analysis method, which introduced the concept of mode excitation degree firstly, then point out that as for the different branch or section, the degree of effect which is caused by disturbance is mainly reflected by the degree of excitation of the oscillation mode. The flow analysis method and the graph theory analysis method, which started from the angel of flow and the topological graph separately, and put forward that the power system is disturbed by the disturbance, the disturbance is spread by the load transfer mode in the power grid [5,6].

With the research on the problem of disturbance propagation being carried out in recent years, some scholars have made a summary of the existing results from different perspectives [7-10]. However, the summary is mainly focused on the analysis method of transient stability analysis and the mechanism of cascading failures. Up to now, nobody make a summary of the problem of disturbance propagation from the perspective of the research method which is used to study the problem of disturbance propagation systematically.

From the angle of research about disturbance propagation, the methods used to study the problem of disturbance propagation be summarized as five methods as follow: time-domain simulation method, transient energy function method, linearization analysis method, flow analysis method and the graph theory analysis method. Meanwhile, every existing method was described in detail from four different aspects: concept, present status and hotspots, critical difficulties, future direction Finally, the future development trend in the field is focused.

2. Time-domain simulation method
The time-domain simulation method is used to analysis the power system through the time response curve of each variable(for example, the rotor angle difference, transmission power and so on) which is obtained by solving the nonlinear differential equation describing the state variable of the power system and the algebraic equations describing the network structure of the system.

The study of large power grid disturbance propagation problem belongs to the category of power system transient stability analysis. As the time domain simulation method can be applied to complex interconnected power system which is composed of a large number of generating units and lines, it can also be applied to all kinds of component models and system failure and operation at the same time. Therefore, it has been widely used and developed in the field of power system transient stability analysis [11-13]. Current time-domain simulation method is mainly focused on the description of the characteristics of the disturbance propagation from the phenomenon level. By introducing the concept of generalized driving energy, reference [14] describes the process of the disturbance propagation from the visual phenomena through the calculation and simulation, and explains the disturbance propagation from the angle of oscillation of cluster coherence and the periodic coupling effect between dominant oscillation modes. Branch potential energy method [15] which is analysis the distribution characteristics of the branch potential energy in the network with time-domain simulation method, and describing the process of disturbance propagation. Energy supply on port method [16] analysis the flow of energy in the power grid after disturbance occurred with time-domain simulation method.

From the current research situation at home and abroad, for the time-domain simulation, the gradual integration speed is slow, the computation is large, and the computation time is long. At the same time, for the study of the disturbance propagation of large power grid, the time-domain simulation method can only describe the level of the phenomenon, but cannot grasp its essence, lack of rational analysis. Therefore, the difficulty of the current research on time-domain simulation method is mainly focused on how to realize its online application, and make a reasonable explanation to the mechanism of large power grid disturbance propagation.

With the wide-area measurement system (WAMS) based on the PMU getting mature, it is a new trend to combine the WAMS with the time-domain simulation method. At present, it is mainly reflected in the following two aspects: (1) to determine the initial value of the calculation, the measurement information of the wide area measurement system can be used as the initial value to improve the accuracy of the simulation; (2) Simplified system model, using the wide area measurement system can realize the dynamic degradation of the system model, reduce the scale of the
power system [17,18], and realize the on-line application of the time domain simulation method. At the same time, taking into account the time-domain simulation method and the transient energy function method, the combination of the two methods can achieve a comprehensive analysis of the problem of large power grid disturbance propagation.

3. Transient energy function method
The transient energy function method which based on Lyapunov stability theory, and analysis the system problems related to power system from the angle of energy system. The transient energy of power system in the stage of failure and the stage of fault cleaning is described by the transient energy function which is expressed by the state of the system. In this paper, In this paper, the transient energy function method is divided into the global transient energy function method and the local transient energy function method.

3.1 Global transient energy function method
By comparing the transient energy of the fault clearance time and critical energy of the system, the transient stability of power system is determined, and the stability margin of the system is given in the global transient energy function method. According to the difference of methods for obtaining critical energy, the global transient energy function method is mainly divided into the unstable equilibrium point (RUEP) method, the potential energy boundary (PEBS) method and the mixed method. For the global transient energy function method, the establishment of the energy function is generally used to simplify the node admittance matrix and the node admittance matrix, and it only pays attention to the relation between the transient energy and the critical energy, the transmission network structure and parameters are implied. Therefore, the distribution of energy in the transmission network cannot be analyzed by global transient energy function method, meanwhile, it could not give the propagation process of transient energy in power grid [19]. However, it provides a new way of thinking for the study of large power grid disturbance propagation problem—with the energy as the carrier, explore the propagation process after the disturbance of the large power grid, that is, after the disturbance of the large power grid occurs, the disturbance energy is transmitted in the transmission network.

3.2 Local transient energy function method
In recent years, a lot of work has been carried out in the research of the distribution law of transient energy in transmission network. Taking into account the work is mainly aimed at the transient energy of each branch after the end of the disturbance, so this transient energy function method is called the local transient energy function method in this paper. It reveals the propagation process of large power grid disturbance from the angle of energy. The power system is subjected to large disturbances (such as short circuit fault, cut off line or machine etc.). System's kinetic energy is formed as the generator rotor is out of balance point. The kinetic energy of the system will be converted into the potential energy of each branch when the fault is removed which is distributed in the augmented network system. With the continuous deterioration of the power grid system, the transient energy of the system will be more and more transferred to the critical cut set of the power grid. The local transient energy method mainly includes the branch transient energy method [15, 19-24] and the energy supply on port method. Both of them can give the expression of the potential energy of each branch and the exchange energy of each port in the course of the disturbance propagation. As shown in formula (1) and formula (2):

\[ V_{\text{res}} \left( \sigma_k \right) = \int_{t_0}^{t_1} \left[ P_1 \left( \sigma_k \right) - P_1' \right] \, dt \]  

\[ V_{\text{res}} \] represents the transient energy of branch \( k \), \( \sigma_k \) and \( \sigma_k' \) represents phase-angle difference of pre- and post-fault of branch \( k \) respectively, \( P_1 \left( \sigma_k \right) \) and \( P_1' \) represents the active power flow of pre- and post-fault of branch \( k \) respectively.
The branch transient energy method is mainly divided into three stages in the study of large power grid disturbance propagation. Stage 1, it is pointed that the transient energy is transmitted in the power grid [20, 23]. Among them, the literature [20] considers that the transient energy injected into the system will attack the branch which is nearest to the fault point. However, literature [23] considers that the order of branch which is attacked is determined by the distance from the branch to the fault point and the generator (near the branch) group inertia time constant, and the development trend of large disturbance impact is analyzed. Stage 2, the distribution law of transient energy in the power system after disturbance is studied, the branch transient energy method considers that with the continuous deterioration of the power grid system, the transient energy of the system will be more and more transferred to the critical cut set [25] of the power grid. Stage 3, the factors affecting the distribution of transient energy in the system are studied, meanwhile, it points out that the distribution of transient energy in the system is closely related to the topology of the network and the operation parameters of the system. The complex interconnected power system is described as a port interconnection structure in the energy supply on port method [26-28], by analyzing the energy flow between each port of the power system, the mechanism of the disturbance in the power network and the influence of the system transient stability are explained reasonably.

On the one hand, for the branch transient energy method, the transient energy is obtained by integrating the actual fault trajectory of the fault system, therefore, the real-time performance is affected. On the other hand, the energy supply on port method can only be used to describe the problem of disturbance propagation qualitatively. The two sides restrict the development of local transient energy function, which is the difficult point of this method.

In recent years, with the improvement of the wide area measurement system (WAMS), real time synchronization data can be obtained from the power grid dispatching center, application of wide area measurement information to local transient energy function method which provides a new idea for the development of the branch transient energy method. Meanwhile, by strengthening the energy structure of each component of the power system, the quantitative description of the generation, dissipation and diffusion of power system transient energy is obtained, to realize the quantitative analysis of the disturbance propagation is the main development trend in the future.

4. Linearization analysis method

Linear analysis method is a basic method for the analysis of small disturbance stability, the system is launched along the trajectory of Taylor after the fault, ignoring the higher order term, the mathematical model of the system is linearized in the vicinity of the operating point. Then the oscillation mode, the mode and the sensitivity information of the system are obtained according to the eigenvalue which is obtained through the linearization of the system.

Early use of linear analysis method to study the problem of disturbance propagation is to use the slow coherency theory [29,30] to determine the coherence unit. This theory is based on the linear model of the power system, and the characteristic roots are obtained by solving the linearized model, then combined with the modal analysis to identify potential unit mode, so as to realize the coherent generators power system identification [31]. The contact section between the coherent generators is the weakest section when the system is disturbed [32]. With the in-depth study of the linear analysis, it
is found that the analysis technique based on the small disturbance stability analysis method cannot accurately reflect the effect of nonlinear and time varying factors of the power system on the damping, oscillation frequency and modal characteristic, etc. And the analysis technique based on the trace characteristic root [33] can reflect the influence of the whole nonlinear and non-autonomous factors clearly, and also can reflect the oscillation, the oscillation center clustering interface and their evolution clearly, it has been widely used and developed [34-37]. At the same time, it also provides a new way of thinking for the study of the disturbance propagation of large power grid. In literature [38], from the perspective of the excitation degree of the oscillation mode which is caused by disturbance, instead of the original nonlinear system, a linear system is used to replace the nonlinear system, then the trajectory characteristic of the perturbed system is calculated by the time stepping method. Meanwhile, according to the matrix which describes the excitation degree of the oscillation mode which is caused by disturbance, the excitation degree of each oscillation mode is calculated. And on the basis of this, a new disturbance impact mechanism is proposed, which is based on the trajectory characteristic root: the oscillation characteristic of the system is determined by the excitation degree of the oscillation mode which is caused by the disturbance.

In the early stage, the signal processing technology is adopted to extract the oscillation mode [39], but for the strong or strong nonlinear time-varying situations, this method is not suitable. The track one by one section characteristic root method [40] proposed that the mathematical model of the nonlinear system is linearized at the starting point of each integral step along the actual perturbed trajectory, then the time series of the characteristic roots of the piecewise linear system is solved. This overcomes the shortcomings of the previous estimation methods which cannot be applied to strongly nonlinear or strong time-varying occasions, but it cannot be applied to the mathematical model or the parameter unknown, and the estimation accuracy is poor. To sum up, the difficulty of the current research on the linear analysis method is mainly focused on how to achieve the accurate estimation of the root of the trajectory characteristics.

Therefore, how to optimize the estimation method of the existing trajectory characteristic root or to find a new method, which can be applied to various occasions to improve the accuracy of estimation, is the main research direction of the future linearization analysis method. Meanwhile, it will be the future research trend to realize the on-line application of the linear analysis method.

5. Flow analysis method
From the perspective of power flow, the development mechanism of cascading failure of power network is: when the power network is running normally, the original load will be distributed on each component of the system. Then some components stop working because of overload, which will lead to changes in the initial power flow of the power system. At this time the original distribution of the load on the components of the outage will be loaded to the rest of the work is still in the normal components, when these rest components cannot withstand the new increase in load, they will stop working, which will cause the redistribution of the load, causing the disturbance to continue to spread in the power grid. Based on the above mechanism, further analysis shows that the power flow distribution of the power grid will affect disturbance propagation characteristics of large power grid. The influence of actual power flow on the disturbance propagation characteristics of large power network is analyzed by the flow analysis method.

The power flow analysis method mainly includes the pattern search method and the model analysis method based on complex system theory. For the pattern search method, the simulation of actual power grid is carried out through the analytic method [41], the stochastic simulation method [42-44] and the hybrid method [45] and so on, then the development path of the power grid cascading failures is searched, which proves that the distribution of the system power flow will affect the propagation of the disturbance in the power network. For the model analysis method, it considers the actual power grid as a system includes a large number of individuals interacting with each other, which realizes the abstraction and simplification of the complex power network. Based on this, the OPA model, the CASCADE model as well as the branching process model and other models were built. The above
models are based on the variation of load, then the development path of the cascading failure is determined by the transfer of the disturbance after the disturbance, so as to realize the analysis of the characteristics of the disturbance propagation.

The stability of the system is not taken into consideration in the current pattern search method and the model analysis method based on complex system theory, which improves the search speed, but the accuracy of the results will be reduced. Therefore, taking the stability of the system into consideration in simulation calculation is the difficulty in the research of the current flow analysis method.

In view of the above problems, the extended equal area method or the transient energy function method can be used in the simulation calculation to judge the stability of the system is one of the development trends of the flow analysis method in the future. Meanwhile, the theoretical modeling is the first step for the power flow analysis method, how to use the existing model to realize the prediction and control of load transfer, and to achieve the prediction of the disturbance in the large power grid, so as to reduce the probability of the occurrence of large power outages is the trend of the future flow analysis method.

6. Graph theory analysis method
First, the graph theory analysis method simplifies the abstract simplification of the real power network into a topological model: the generator, load and substation in the power grid are described as joints, the sides of graph are the high voltage transmission lines. Then, based on the topology structure of the actual power grid, the influence of the network on the disturbance propagation characteristics of the large power network is analyzed.

In literature [46], the power network is abstracted as a complex network, starting from the perspective of power grid topology, the impact of the deliberate attack and the different types of random faults on the real power network is studied, then the corresponding model and algorithm are put forward, and combining with a certain regional power grid, the influence of the topology of the network on the disturbance propagation is analyzed. In literature [47], by comparing the typical grid topology of China and the United States, the influence of small world network characteristics on the disturbance propagation of large power network is analyzed qualitatively, the result shows that most of the power networks belong to small world networks. Meanwhile, it points that with the characteristics of high clustering coefficient and small average distance, the small world model will play a bad role in the propagation of the disturbance. Small world model is introduced in literature [48] and [49], the cascading failures of China Power Grid and North American power grid are simulated respectively, the effect of the important joints and the circuit on the occurrence and expansion of the cascading failures is pointed out. With the deepening of the research, the Holme and Kim model [50], the Motter and Lai model [51], the Crucitti and Latora model [52] are introduced to the study about the influence of power grid topology on the propagation characteristics of large power networks.

By using the method of graph theory to study the problem of disturbance propagation, the influence of the topology of network on the disturbance propagation is only considered, in fact, the current state of the power system will affect the disturbance propagation. Therefore, considering the influence of the network topology and the operating state of the current system on the disturbance propagation is the difficulty of the current graph theory analysis method.

The operation parameters, main wiring structure and the secondary system of the power grid are greatly influenced by the action of relay protection. However, these factors are often ignored in the analysis of the problem by graph theory, so how to take these factors into account is the trend of the future research of graph theory analysis method.

7. Conclusions
Studying the problem of disturbance propagation and curbing the occurrence of large electric power accidents are still the focus of the study of UHV power grid era, the future research should be started from the following points:

(1)Multiple hybrid methods: The time-domain simulation method is combined with the transient
energy function method, the RUEP method is combined with the PEBS method and the EEAC method, and learn from each other, forming a method with faster calculation speed and high accuracy analysis, which is propitious to practical application of the method of time domain simulation and transient energy function method in engineering. The flow analysis method is combined with the graph theory analysis method, the dynamic characteristics of large power network are considered in the micro level by the power flow analysis method, and the graph theoretic analysis method considers the influence of the topology of the power grid on the disturbance propagation from the macroscopic view. By combining these two methods, we can know more about the disturbance propagation in large power grid.

(2)The introduction of artificial intelligence methods: Considering the power system is characterized by large scale, high nonlinearity and close relationship among the components in the system, the general method is difficult to realize the research of large power grid disturbance propagation problem. Taking into account the intelligent method to allow the model the accuracy of nonlinear system adaptive, self-learning, adaptive and self-organizing characteristics, the artificial intelligence method can be introduced into the study of large power grid disturbance propagation problems in the future.

(3)Introduction of wide area measurement information: With the improvement of the wide area measurement system (WAMS), real time synchronization data can be obtained from the power grid dispatching center, the wide area measurement information is introduced into the study of the disturbance propagation, which can be used to realize the on-line analysis of large power grid disturbance propagation.

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