Study on technology system of self-healing control in smart distribution grid

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Abstract: Smart distribution grid is an important part of smart grid, which connects the main network and user-oriented supply. As an “immune system”, self-healing is the most important feature of smart grid. Major problem of self-healing control is the "uninterrupted power supply problem ", that is, real-time monitoring of network operation, predicting the state power grid, timely detection, rapid diagnosis and elimination of hidden faults, without human intervention or only a few cases. First, the paper describes major problems, which are solved by self-healing control in smart distribution grid, and their functions. Then, it analysis the structure and technology components of self-healing control in smart distribution grid, including the base layer, support layer and application layer. The base layer is composed of the power grid and its equipments, which is the base for smart grid and self-healing control. The support layer is composed of the data and communication. High-speed, bi-directional, real-time and integrated communications system is the basis of achieving power transmission and the use of high efficiency, reliability and security, and the basis for intelligent distribution network and the key steps of self-prevention and self-recovery in distribution grid. The application layer is composed of Monitoring, assessment, pre-warning/analysis, decision making, control and restoration. Six modules are interconnected and mutual restraint. The application layer is important means of self-prevention and self-recovery in distribution grid. Through the research and analysis on the relationship and the technical composition of six modules in the application layer, the paper divides running states of smart grid distribution grid having self-healing capabilities into five states, which are normal state, warning state, critical state, emergency state and recovery state, and defines the characteristics and the relationship of each state. Through investigating and applying self-healing control in smart distribution grid, smart distribution grid can timely detect the happening or imminent failure and implement appropriate corrective action, so that it does not affect the normal supply or minimize their effects. Power supply reliability is improved observably and outage time is reduced significantly. Especially in extreme weather conditions, the distribution grid will give full play to its self-prevention and self-recovery capability, give priority to protecting people's life and provide electricity for the people furthest.

Keywords: smart distribution grid, self-healing control, technology system

1 Introduction

In the 21st century, the concept of smart grid has been erminated and formed gradually, which has become a common choice to face future challenges. At present, China and the world have reached a consensus that building a flexible, clean, safe, economical and friendly smart grid is the future direction of the grid. Smart grid can achieve security, stability, high quality, reliable, and economic environment of power system, and is an important strategy for sustainable supply protection, with the integration, optimization, distribution, coordination, interaction, and self-healing characteristics [1-5].

Smart grid includes generating electricity, transmission, distribution and consumption. According to the current international and domestic research, smart grid mainly includes four parts, which are advanced distribution operation, advanced measurement system, advanced transmission operation and advanced asset management. In each part, advanced distribution equipment is relatively weak, so the distribution grid is the focus of everyone's attention in the international study in the smart grid [6]. Smart distribution grid is an important part of smart grid, which is connecting the main network and users [7].

Smart distribution grid helps to improve power supply reliability, system operating efficiency and power quality terminal. It also contributes connecting into the grid and optimal operation of distributed generation, energy storage and micro-network in order for efficient interaction of demand-side management. With advanced modern management concepts, smart distribution grid builds integration and optimization system of distribution assets operation, maintenance and management. Smart distribution grid is stronger and has a greater flexibility than traditional distribution grid. It can effectively resist the impact of external damage such as natural disasters and emergencies. Smart distribution grid has a strong "self-healing" function. Self-healing is the most

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important features of the smart distribution grid. In essence, self-healing is "the immune system" of the smart distribution grid. At present, domestic and foreign scholars are actively exploring the self-healing grid architecture [8-10], self-healing control system and control strategy [11, 12]. However, these studies have not yet formed a unified systems theory, nor for self-healing control study of smart distribution grid. The paper researches on the technology system of self-healing control in smart distribution grid. First, it analysis the hierarchy of self-healing control system designation in smart distribution grid, which is divided into three layers, namely: base layer, support layer and application layer. Secondly, the paper analysis the technical components of each layer.

2 Overview

The "self-healing" capability of smart distribution grid is that it can be able to timely detect the failure occurred or occurring, and the corresponding corrective action is adopted, in order not to affect the user's normal power supply nor reduce the impact to Min. With little or no human intervention, self-healing control is mainly to solve the "problem of uninterrupted power supply", that is, monitoring the grid, the real-time operational status, predicting the state of power grid, timely detection, rapid diagnosis and elimination of the hidden faults. Self-healing control in smart distribution grid will have a higher reliability and a higher power quality. It supports a larger number of distributed energy connection, supports the user energy management, improves network asset utilization, does visual management for distribution grid and its devices, and achieves automation and information technology of distribution grid equipment management and production management.

3 Technology System

Technology system of self-healing control in smart distribution grid is divided into three levels, namely: the base layer, the support layer, the application layer.

3.1 Base Layer

The power grid and its equipments, including physical network, intelligent switches, intelligent power distribution terminal, protection and control equipment, distributed energy and micro-network, compose the base layer.

As the physical carrier of the smart grid, physical grid and its equipments are the foundation of achieving smart grid and self-healing control [13]. In view of the low levels of distribution grid in China compared with foreign advanced countries, our distribution network should be based on reliable intelligence as the core, run for the goal of efficient distribution grid, increase the load level of management and user involvement at the same time. Moreover, a large number of distributed energy and other forms of clean energy will connect into the power grid in future, so distribution grid must have the ability of current optimization, reconstruction of network, and accepting clean energy. Meanwhile, with the increasing of distributed energy, especially with extensive use of rooftop solar power and electric vehicles, the bidirectional interactivities of grid electricity flow and information flow will gradually increase, which will have significant impact on grid operation and management. Therefore, in the construction process of physical distribution grid, we must be forward-looking exploration, planning and building. We must have a long-term vision to study the development of our distribution grid, vigorously promote innovation of advanced technology, and actively adopt mature advanced technology in order to meet the needs of future smart grid in the architecture, technology, and equipment of the physical grid.

3.2 Support Layer

The support layer is data and communication, which consist of high-speed two-way real-time integrated communications technology, open communication architecture, a unified technical standards and comprehensive security measures.

Information exchanging covering the entire grid is the base of achieving power transmission and using efficiency, reliability and security [14]. Moreover, self-healing control needs to collect status data and meter measurement data of equipments. For such large number and scattered collection point situation, we need to establish a high-speed, bi-directional, real-time, integrated communications system by high-speed two-way real-time integrated communications technology, open communication architecture, a unified technical standards and comprehensive security measures.

The high-speed two-way real-time integrated communications technology is the basis for building the smart distribution grid, but also the key steps into self-prevention and self-healing of the distribution grid. After the completion of such communication systems, power grid achieves its self-healing capacity, improves the ability to control the power grid and the service level, through continuous self-monitoring, correction and the application of advanced information technology. It can also monitor a variety of disturbances, compensate reactive power, re-distribute the trend, and avoid expansion of accidents.

3.3 Application Layer

Various functions of self-healing grid is depending on using techniques, such as monitoring, assessment, early warning, policy-making, control, and recovery, to achieve self-prevention and self-healing of power grid, on the base of improving power grid, electrical equipment and data communications. The paper describes application layer functions of the technology system of self-healing control in smart distribution grid from the above six aspects. The relationship of each functional module is shown in Figure 1.

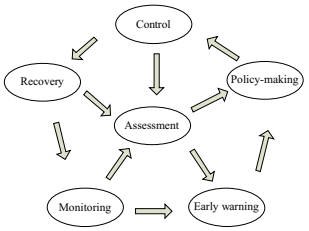

Figure 1 Relationship of each state in the application layer.

Through the research and analysis on the relationship and the technical composition of six modules in the application layer, the paper divides running states of smart grid distribution grid having self-healing capabilities into five states, namely normal state, warning state, critical state, emergency state and recovery state.

Characteristics of each state are shown in Table 1, and the relationship of each state is shown in Figure 2.

Table 1 Runing feature map of self-healing control in smart distribution grid

State	Feature
Normal state	Indicator of each parameter within the allowable range
Warning state	The parameter index is not beyond the limits, but some indicators are in the warning area
Critical state	Some indicators of system operating parameters are in a critical state
Emergency state	Some of the important parameter index of the system are beyond the limits
Recovery state	Part-load's power supply is interrupted

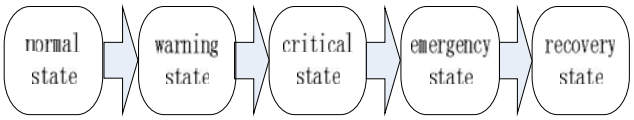

Figure 2 State diagram of self-healing control in smart distribution grid.

3.3.1 Monitoring

Smart distribution grid is a complex system. According to the view of modern control theory, the system must be able to observe first in order to effective control a system [15]. Self-healing control in smart distribution grid focuses on improving the observability and controllability of power grid, and enhancing the monitoring role of the electrical device parameters, power running state and distributed energy, which will need a more high demand of sensing and measurement technology.

The sensing and measurement technology includes smart sensors, synchronized phasor measurement technology, power grid condition monitoring equipment, distributed energy monitoring equipment, and meters, transformers, feeders, switches, etc.

(1) Smart sensors

Smart Sensor is a kind of sensor with a microprocessor, information detection, information processing, information memory, logical thinking and determining. Smart sensors provide a sensitive "nerve endings" for the self-healing distribution grid. In order to monitor most of the equipment in the smart grid, smart sensors used must have a high cost, small size, good engineering and maintenance, good electromagnetic compatibility and intelligent data exchange interface features, and be easy to install, promote and maintain.

(2) Synchronized phasor measurement technology

Global Positioning System (GPS) provides a precise time for synchronized phasor measurements. It can carry on the synchronized phasor measurement, real-time recording, transient wave recording, clock synchronization, operating parameters monitoring, real-time data and transient data analysis. It can also achieve the simultaneous measurement of each node [15], transport measurement phasor to the main station by high-speed communications networks, and provide basic information of real-time monitoring, analysis and control the bulk power system.

As the Phasor Measurement Unit (PMU) can achieve real-time simultaneous measurement of wide-area network running state, it creates the conditions for global stability of the overall power system stability control, overcomes the shortcomings of not monitoring and identifies the power system dynamic behavior through the existing scheduling monitoring system represented by SCADA, and improves the results of the traditional state estimation. With the development of smart distribution grid, it requires more complex controlling and protection systems. So real-time phase angle measurement system will be essential in these control and protection systems. Although the PMU has not been applied in the distribution grid, the author believes that the application of PMU is inevitable in smart distribution grid.

(3) Power grid condition monitoring equipment

Using power grid condition monitoring equipment can monitor power grid running state, displays it accurately, and uploads the grid current dynamic running data timely.

(4) Distributed energy monitoring equipment

Distributed energy monitoring equipment carries on real-time monitoring, control and management for distributed energy terminal, real-time displaying terminal parameters, and providing real-time data for the evaluation module and the early warning module. Meanwhile, it can achieve remote meter reading timely, inquiry historical curve various reports automatically, reducing staff labor intensity, avoid human error, avoid disputes, and improve the management level.

(5) Meters, transformers, feeders, switches, etc

In addition to smart sensors and synchronized phasor measurement technology, measurements in smart distribution grid of the future may be over the grid meter, transformers, feeders, switches, other equipment and devices.

3.3.2 Assessment

Traditional distribution grid assessment methods are mostly

from the ability of power supply and the grid structure. Due to the complexity of the smart distribution grid, its assessment should be coupled with grid security assessment, equipment condition assessment, grid vulnerability assessment, grid risk assessment and tariff grid adaptation assessment on the base of traditional distribution grid assessment, so that it can reflect the actual situation as much as possible for early warning and self-healing grid decision-making.

(1) Grid security assessment

Power system security means that the ability to withstand the fault disturbance when the power system is in operation. With the development of smart distribution grid and distributed energy connection, the power system structure and the operation are becoming complex and the impact of failures caused by system instability is broader. In this case, it is necessary to do static security assessment and dynamic security assessment for power grid.

(2) Equipment condition assessment

The reliability of self-healing distribution grid depends largely on the reliability of electrical equipments. Electrical equipments are the main vehicle for grid operators. Their health status will have a direct relationship to the ability of resist risks. Equipment condition assessment can continually real time update assessment based on device operating parameters changing, and quantify the status of the device, so that the assessment results can be self-renewal and improved with the modification of the device and the line. It can also play a long-term, dynamic and effective guiding role for analyzing the equipment security, the power system possible failure rate and its trends.

(3) Grid vulnerability assessment

Self-healing control in smart distribution grid emphasize the fragile state and attaches importance on prevention control. It means assessing the vulnerability of the grid. That is to say, according to the severity and different categories of the vulnerability, targeted control program is adopted. Vulnerability assessment is to assess the possible changes by external force or emergency circumstances, that is, the sensitivity to face of unexpected events and losses that may occur. So, doing the vulnerability assessment will be able to timely and effectively forecast and early warn of possible future trends or loss, inhibit the development of negative factors, recover and reconstruct the damaged system as quickly as possible, in order to achieve the sound development and sustainable use of the system.

(4) Grid risk assessment

As an important analysis and evaluation tools in smart distribution grid, we should pay attention to risk assessment in the early construction of smart distribution grid. Smart distribution grid introduces a number of new components and equipments, and has brought a new structural adjustment. It makes risk analysis more complex. Because systemic risks caused by traditional equipment failure still remains, a lot of new equipment running statistical data lack, traditional equipment and new equipment have to coordinate, and smart distribution grid causes structural changing. For these reasons, we need to do quantitative assessment and management for risk in order to reduce risk from the controllable factors.

(5) Tariff grid adaptation assessment

Smart distribution grid has the ability of interaction with customers. The power grid can provide customers with real-time electricity pricing and information, guide customers use electricity rational and efficiently, improve energy efficiency, and achieve power optimization, diagnostic efficiency, and so on. However, electricity load changes greatly by the influence of the price, which has an impact on the capacity of the power grid. Therefore, we need to assess the suitability of the tariff.

3.3.3 Early warning

Smart distribution grid is large and operation mechanism is complex. However, practice shows that there is a gradual process for the majority of failures except for a few other unexpected failures. It is completely preventable by acting appropriately. If early detected and appropriate measures are timely adopted, they are completely preventable. In order to detect grid security risks and improve grid self-healing capabilities, warnings and treatment measures are raised for failures that may occur in the grid on the base of power state assessment according to the power grid information and environmental changes. It is early warning. Early warning is an integral part of self-healing grid. It achieves power line running tracking automatically, can detect grid problems, and gives early warning signals automatically.

Early warning technology system includes trend forecasting techniques, early warning analysis, event/alarm filtering technologies, emergency alarm technology, events forecasting methods, ultra-short-term load forecasting techniques, hidden failure monitoring techniques, early warning indicator system, rapid series of events predicted and the protection given value-line tuning.

When the grid reaches an early warning status, self-healing control system through early warning technology system makes the implementation of comprehensive and integrated real-time warning for the security of power grid. In order to take proactive measures for eliminating security risks in the early stage, it automatically tracks power grid security level, automatically extracts features information of the power system state, automatically discovers serious accidents, detects a variety of security risks in the grid, and makes early warning.

3.3.4 Policy-making, control, and recovery

Assessment and early warning information uploads to the policy-making layer. There are fault diagnosis technology, fault location and isolation technology, power flexible partitioning technology, self-healing decision-making visualization techniques and the corresponding models, algorithms, rule base, knowledge base in policy-making, control, and recovery. Through these technologies, self-healing control system is ready to take technical measures to eliminate the

results of the initial cause of just consequences, and start a reaction cause chain to offset the effects of the causal chain of the failure, which can suppress the fault in the bud and control, restore, and maintain the stable operation of the power grid.

Corresponding to the five running state of power grid, there are four basic control techniques, namely: prevention and control techniques, calibration control, emergency control and recovery control..As smart distribution grid has the ability of accepting distribution energy, in addition to the above four basic control technology, we need to study on distributed energy integration technology, control mode of smart distribution grid, self-healing control visualization technology, distributed coordination / adaptive control technologies.

When the power grid runs to recovery state, power supply has been interrupted in some areas. In order to meet the needs of safe operation, we have to reject part of the load. Therefore, we need to study on model update technology, rapid reconstruction of the network technology, frequency stabilization, adaptive reject load technology, self-healing splitting technology, and self-healing recovery simulation technology.

4 Conclusion

As an “immune system”, self-healing is the most important feature of smart grid. By studying and application self-healing control technology in smart distribution grid, power supply reliability will be improved observably and outage time is reduced significantly. Especially in extreme weather conditions, the distribution grid will give full play to its self-prevention and self-recovery capability, give priority to protecting people's life and provide electricity for the people furthest.

1 YU YiXin, LUAN WenPeng. Smart grid[J]. Power System and Clean Energy. 2009, 25(1): 7-11.

2 XIE Kai, LIU YongQi, ZHU Zhizhong, et al. The vision of future smart grid[J]. Electric Power, 2008, 41(6): 19-22.

3 YOU H, VITTAL V, YANG Z. Self-healing in power system: an approach using islanding and rate of frequency decline-based load shedding[J]. IEEE Trans on Power Systems, 2003, 18(1):174-181.

4 AMIN M. Toward self-healing energy infrastructure systems[J]. IEEE Computer Applications in Power, 2001, 14(1): 20-28.

5 AMIN A. EPRI/DOD complex interactive network/systems initiative: self-healing infrastructure// Proceedings of the 2nd DARPA-JFACC Symposium on Advances in Enterprise Control, July 10-11, 2000, Minneapolis, MN, USA.

6 HUANG Sheng. Analysis on the demand for communication services in smart distribution network and communication technical scheme[J]. Telecommunications for Electric Power System. 2010,31(212): 10-12,17.

7 LU YiMing, LIU Dong, LIU JinSong, et al. Information Integration Demand and Model Analysis for Smart Distribution Grid. Automation of Electric Power Systems[J]. 2010,34(8): 1-4,96.

8 CHEN XingYing , GU XinXin , YU Kun , et al. Architecture for Self-healing Control of Urban Power Grid. Automation of Electric Power Systems, 2009, 33(24):38-42.

9 GU XinXin, JIANG Ning,jI Kan, et al. Practice and Prospects of Self-healing Control of Intelligent Distribution Grid. Electric Power Construction, 2009, 30(7):4-6.

10 MOSLEHI K, KUMAR A B R, SHEURTLEFF D, et al. Framework for a self-healing power grid// Proceedings of IEEE Power Engineering Society General Meeting, June 12-16, 2005, Montreal, Canada.

11 GUO ZhiZhong. Scheme of self-healing control frame of power grid [J]. Automation of Electric Power Systems, 2005, 29(10):85-91.

12 GU Xinxin , JI Kan , CHEN XingYing , et al. Brief Discussion on the set-up of a highly reliable urban power network[J]. Distribution & Utilization, 2008,25(24):4-7.

13 [MIAO Xin, ZHANG Kai, TIAN ShiMing, LI JianQi, YIN ShuGang, ZHAO ZiYan. Information Communication System Supporting Smart Grid [J]. Power System Technology. 2009,33(17):8-13.

14 YANG MingHai, WANG ChengShan. Survey for Optimal PMU Allocation in Power System. Proceedings of the CSU-EPSA, 2007,19(2):85-92.

15 Xu DongJie, He RenMu,Wang Peng,et a1.Compar-ison of several PM U placement algorithms for state estimation1[C]//Eighth IEE International Conference on Developments in Power System Protection, Amsterdam, Holand, 2004(1)：28-31.