

Integrated Wide Area Protection and Control for Power Grid Security

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Abstract—The traditional “three defense lines” for power systems are based on local information and static protection & control strategy, which are not suitable to modern large-scale power systems. In order to improve the security of UHV hybrid power grids, the Integrated Wide Area Protection & Control (IWAPC) is proposed in this paper by applying the new technologies of synchronized high-speed communication, which integrates “three defense lines” and promotes existing wide area protection only for security control. The IWAPC is the hierarchical protection and control system which provides the protection and control for wide area power networks to improve their reliability and security. It is divided into three levels, the local bay level, the substation integrated protection level and the wide area protection level. The wide area real-time protection and control information platform is the most important part of the IWAPC, which is based on a synchronized wide area communication network. The key technologies and new development trends include network topology analysis, wide area backup protection, wide area intelligent reclosing, wide area load shedding, wide area auto-switching, overload cutoff and transfer, transmission section protection, intelligent system splitting and dynamic stability control. It cannot only integrate three lines of defense for power system protection and control, but also improve security of the power grid.

Index Terms—Digital substation, power grid security control, system protection, wide area protection & control.

I. INTRODUCTION

THE new technologies, such as large-scale renewable generation, AC/DC hybrid transmission, ultra-high voltage transmission, flexible AC transmission, and multi-terminal HVDC, have been applied rapidly in modern power grids, which has caused the more complex in transient behavior, the impact of the partial failure increased significantly, and may even rapidly threaten the network throughout, which greatly increases the difficulties for protection. However, the present protection and controls are still at the level for individual elements, which makes it difficult to achieve system-level fault self-healing, automatic optimization and adjustments. Meanwhile, the existing element protection with the limitations of local information, cannot meet the requirements

of the modern power grid. The backup protection requires further optimization to improve the reliability, selectivity and sensitivity.

The progress in modern technology helps to stimulate the ongoing development in power system protection [1]. Particularly, the application of novel communication techniques and the utilization of a global positioning system (GPS) in power system protection marked the start of new developments in recent years [2].

In this respect, a number of new techniques have been proposed. In particular, the new proposed protection relay principles are able to provide protection for wide area power networks [3], [4]. The wide area protection which has been presented focuses on power system control [5]. In recent years, the development of signal processing and communication technologies for relaying protection platforms provided a new opportunity to revisit centralized wide area protection. The “Integrated Protection” in research [6] shows that it can develop new protection principles and schemes based on information from multiple substations and components. In this respect, the substation area protection [7] has quickly become a practically developing and applied area. Furthermore, the development of information technology has resulted in the interests in utilizing cloud computing [8] and big data techniques to improve the performance of power system protection and control.

The increased deployment of wide area measurements will significantly enhance the wide area power system operation and control. A wide range of power system monitoring and control applications can be implemented in the system for improving system awareness and reliability, which include enhanced state estimation based on mixed Remote Terminal Unit (RTU) and Phasor Measurement Unit (PMU) measurements [9], [10], dynamic model online estimation and validation [11], real-time congestion management, real-time stability estimation [12], and detection and damping of inter-area oscillations [13]. But, the most important and challengeable application is the implementation of wide area stability real-time detection and control to prevent blackouts [14].

The functions, control, models and system structures of Wide Area Protection are discussed in [15], [16], which include wide area protection equipment and systems at different levels. There were also important developments in recent years in the integrated wide area protection [17] and integrated protection and control [18]. The Wide Area Differential Protection [19] and Wide Area Backup Protection [20] are

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proposed to improve the performance of existing protection. The research and engineering practice of wide area protection and control systems are discussed to bring out several urgent problems for improving wide area protection technology [21].

By analyzing the limitations of traditional “three defense lines,” the Integrated Wide Area Protection & Control (IWAPC), or the System Protection in brief for integrating the “three defense lines,” are proposed in this paper. It is divided into three levels, the local bay level, the substation integrated protection level and the wide area protection level. The integrated functions are described in detail with an aim to develop an optimal coordination mechanism between the different levels. The key technologies and new researching trends are presented in this paper, including network topology analysis, wide area backup protection, wide area intelligent recloser, wide area load shedding, wide area auto-switching, overload cutoff and transfer, transmission section protection, intelligent system splitting and dynamic stability control. It cannot only integrate the three lines of defense for power system protection and control, but also improve the security of the power grid.

II. TRADITIONAL “THREE DEFENSE LINES” THEORY AND ITS LIMITATIONS

The “three defense lines” has been widely used in power systems. The “three defense lines” is a concept of the whole security defense system for power systems [22].

- 1) The first line is the protection relay system;
- 2) The second line is the stability and security control including generator rejection and load shedding;
- 3) The third line is the separation relay after loss of synchronism followed by the frequency and the voltage emergency control.

The “three defense lines” of power grid stability is designed to prevent the electric power system from reaching unstable status as shown in Fig. 1. As the most efficient method, the first line of defense is to guarantee the power system transient stability by rapidly removing the fault component using a relay protection device. The second line of defense is to ensure the stability of the power system under great disturbance by using stability control devices, generator tripping and load shedding. The third line of defense is to maintain the power

balance of the separated power system after splitting, which can prevent the accidents from causing a system collapse by using frequency and voltage emergency control devices when serious damage is occurring.

The traditional “three defense lines” for a power system is based on local information and a static protection & control strategy, which is not suitable any more to modern power systems. Its limitations include: information islanding caused by separated stability control systems; in-coordination between protection and control for different devices; static setting and configuration of protection & control which cannot meet the new requirements of power system security.

III. INTEGRATED WIDE AREA PROTECTION & CONTROL

The basic architecture of an IWAPC system is shown in Fig. 2. There have been fast developments in both power transmission and distribution networks in recent years, for example FACTS and HVDC in transmission systems, and distributed generations and micro-grid in distribution systems, etc. These new developments cause the modern power grid to have more complicated characteristics than conventional systems. Therefore, the existing protection is not effective anymore. The IWAPC system is necessary for future power systems [23]. Some integrated protections based on transient information are proposed for distributed generations and micro-grids in distribution systems [24], [25]. They can be realized based on the IWAPC system.

The IWAPC system primarily consists of three levels of equipment which are the integrated “all-in-one” IEDs at the local bay level, the integrated substation protection at the substation level and the wide area protection & control at wide area level. The wide area synchronization communication network is another important part of IWAPC, which includes the substation communication network and the integrated wide area communication network. The IWAPC based on integrating the “three defence lines” in this paper provides significant improvement to traditional wide area protection. It not only can implement security control based on wide area information, but also integrate coordinative functionalities at different levels including protection, automation and system stability control in substation and protection & control centers.

The IWAPC can be extended to achieve the integration of relaying protection, security control and substation automation of power systems, including the functionalities of regional protection, control and advanced applications. The IWAPC proposed in this paper is totally different from the traditional “three defence line.” The functionalities of IWAPC are allocated to different levels according to the region of information gathering and sharing. The functionalities of information acquisition and main protection based on local bay information are defined in the local level, which are implemented in “All-in-one” IEDs in digital substations. The substation protection and control integrate backup protection and substation control based on substation information are located in the substation level, such as automatic bus transfer, circuit breaker failure protection and load shedding. Some functionalities based on regional information are implemented in the wide area protection level, including voltage and frequency control, etc.

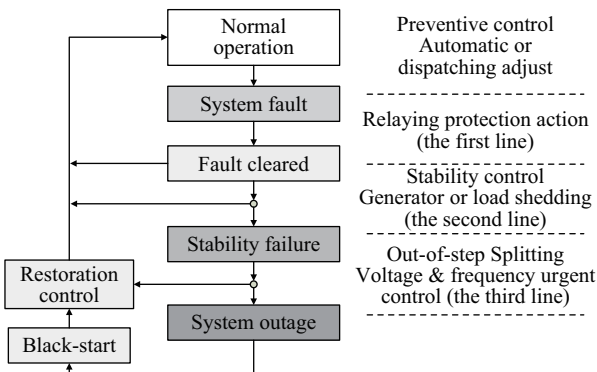


Fig. 1. “Three defense lines” for power grid security.

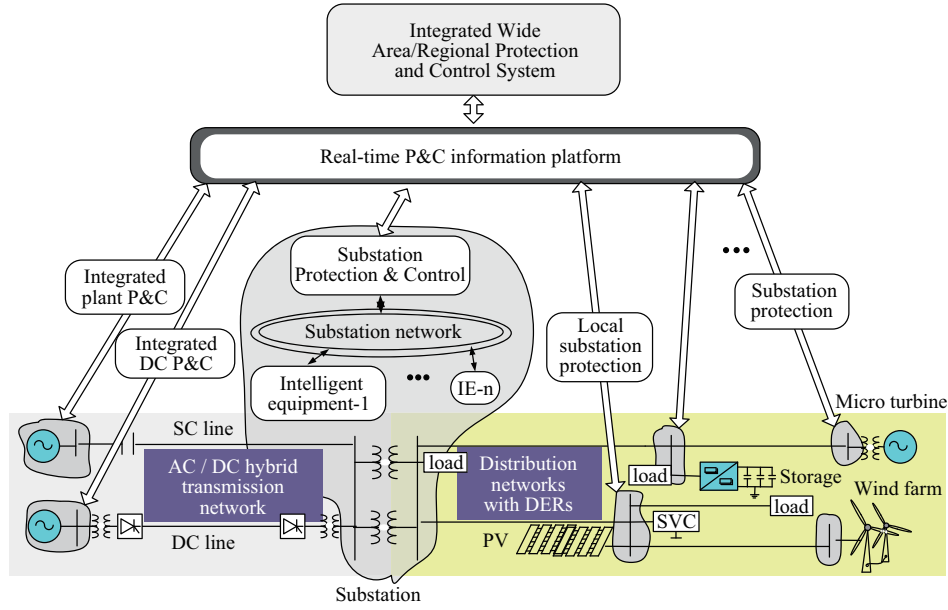


Fig. 2. Architecture of Integrated Wide Area P&C.

A. “All-in-one” IED in the Local Level

“All-in-one” IED in the local level is the basis of IWAPC, as shown in Fig. 2. The “all-in-one” device is developed, which integrates the functionalities of the merging unit, intelligent terminal and local protection for a single bay. The structure of the “all-in-one” device is shown in Fig. 3. There are different interfaces for conventional electro-magnetic transformers and also unconventional such as merging units. The monitoring and control of breakers & switches are realized digital input/output interfaces. The “all-in-one” device supports Sample Value (SV) communication following IEC61850-9-2 and the Generic Object Oriented Substation Event (GOOSE). Some functionalities of protection & control, which belongs to the bay logic level, are implemented in “all-in-one” devices to improve reliability of the protection & control system in case of communication failure. Only protection and control based on single bay information can be configured in a “all-in-one” device, such as line protection based on the current differential relay, distance relay and overcurrent relay. The “all-in-one” devices should be installed nearby the primary equipment.

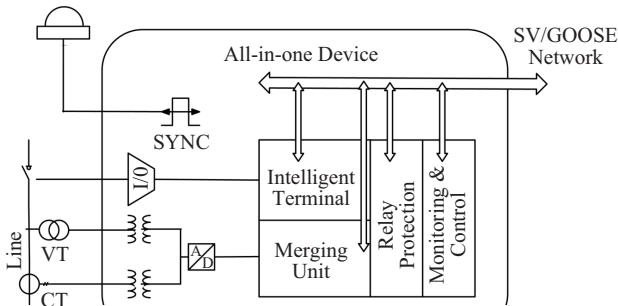


Fig. 3. Structure of “all-in-one” IED in the local level.

According to the principle of IWAPC, the existing functionalities of the local protection are optimized. Only main pro-

tections based on local fault information are reserved in local “All-in-one” IEDs. The standby backup protection & controls are available only in the condition of a substation protection failure. The optimal functionalities of the transmission line protection are shown in Table I and Table II for example. Table I shows the functionalities of the traditional local protection; Table II shows the optimal functionalities of the local IED.

TABLE I
THE FUNCTIONALITIES OF TRADITIONAL LOCAL PROTECTION

P & C	Function
Current Different	IPh high impedance differential protection
Current protection	Instantaneous phase overcurrent protection
	Four step phase overcurrent protection
	Instantaneous residual overcurrent protection
	Four step residual overcurrent protection
	Directional negative phase sequence overcurrent protection
	Sensitive directional residual overcurrent and power protection
	Thermal overload protection, one time constant
	Thermal overload protection, two time constant
	Breaker failure protection
	Pole discordance protection
Voltage protection	Directional under power protection
	Two step under-voltage protection
	Two step overvoltage protection
	Two step residual overvoltage protection
	Voltage differential protection
Frequency protection	Loss of voltage check
	Under-frequency protection
	Over-frequency protection
	Rate-of-change frequency protection
Control	Auto reclose
	Synchrocheck, energizing check and synchronizing
	Automatic voltage control for tap changer

B. Substation Protection & Control in the Substation Level

The substation protection & control does not only integrate the backup protection of the transmission line, bus and transformer, but also implements functions of the sub-

TABLE II
THE OPTIMAL FUNCTIONALITIES OF LOCAL IED

P & C	Function
Main protection	1Ph high impedance differential protection
Standby protection	Four step phase overcurrent protection
	Four step residual overcurrent protection
	Thermal overload protection
	Pole discordance protection
	Two step undervoltage protection
	Two step overvoltage protection
Standby control	Auto reclose
	Synchrocheck, energizing check and synchronizing
	Automatic voltage control for tap changer

station control, including automatic reclosing, automatic bus transfer, circuit breaker failure protection, low-frequency and low-voltage load shedding, overload inter-tripping, etc. The substation backup protection and safety automatic controls are realized by the entire substation information. The stage overcurrent protection, breaker failure protection and dead zone protection in the conventional protection system are substituted by the extended current differential protection.

In order to improve the reliability of the main protection, the functionalities of the local IED are substituted by the standby functionalities of the substation protection level on the basis of local IED failure or maintenance. The local main protections are substituted by the substation protection shown in Fig. 4, which is very useful without a duplicated arrangement.

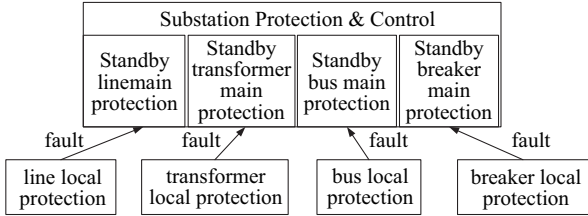


Fig. 4. The substitution of local main protection by substation protection.

C. Integrated Wide Area Protection and Control

The integrated wide area protection and control are integrated functions of backup protection and security control. Some functions can be achieved at both the substation and regional protection & control center, such as low-frequency and low-voltage load shedding, voltage and frequency control, and automatic bus transfer. The function of transmission cross section safety P&C can be realized by the IWAPC based on sharing information of the regional power grid, which includes oscillation detection and out-of-step separation. In addition, the IWAPC integrates protection and control into one optimal combined system compared to traditional protection. It can coordinate the regional protection and control effectively and make great improvements to the power system protection.

IV. SYNCHRONIZED COMMUNICATION PLATFORM

A. Communication Network Based on PTN

The high-speed communication network is the basis of the IWAPC system. The present communication network of a

power system is based on the Synchronous Digital Hierarchy (SDH) communication network, which is a multi-service communication platform [26]. The advantages of SDH are high efficiency, low latency and high reliability. But it also causes many problems, including poor flexibility and low bearing efficiency for data services implementation. The advanced SDH optical fiber self-healing ring network can usually meet the demands for network communications in real time and dependability. Based on multi-protocol label switch (MPLS) traffic engineering, the specificity problem in the wide area protection communication system can be solved, including the quality of service (QoS) requirements and the path selection of traffic balancing [27].

But the Packet Transport Network (PTN) is more suitable for use with wide area protection and control. Compared to SDH, PTN is a based Packet-switched technology to realize statistical multiplexing and efficient transfer of packet service. It can improve the rigid bandwidth and provide better quality of operation, service and administration. The synchronized timing based on IEEE-1588 technology is used for the integrated wide area protection and control.

B. Synchronized Information Platform

A substation installs a wide range of electrical equipment, with complex design and it is difficult to maintain. With the continuous improvement in power system automation and the intelligence level, the system network has been expanding, so there is a huge amount of information in protection and control. Because each piece of information is collected and stored by different devices to each separate system, the interoperability of the internal power system data between systems is poor, requires complex communication protocols, and forms information islands. This result is the measurement data and protection control mechanism cannot be shared, which restricts the information integration. The protection and control of the smart grid has requirements to deal with and demands for new situations of the application; further improving of the information platform capabilities for the future rapid development provides key technologies; making the information platform system more open.

The real time synchronized information platform accurately collects wide area information [28]. In the platform, the sets of data that need to be transferred and their transferring speed depend on the applications, for example, slow for contingency analysis, near real time for monitoring and real time for control, and high speed for wide area protection, in particular time synchronization. On the other hand, the information is stored in a hierarchical manner instead of a centralized one, which is comprised of the hierarchical protection and control system.

The introduction of advanced computing technology allows for building a synchronized information platform for wide area protection and control, building a panoramic operation and maintenance data collection network, providing a standardized interface to the terminal device for forming a resource sharing, flexible and interactive, open and orderly information platform. In summary, advanced computing technologies are used to build a distributed collaborative intelligent information

platform, simplifying terminal data collection equipment, and breaking the barriers between protection and control systems at different substations through the specially designed synchronized information platform.

Based on the synchronized communication platform, a distributed information system is designed to support the Integrated Wide Area Protection & Control, as shown in Fig. 5.

These functions based on regional sharing information include the wide area fault line selection, wide area fault location, power quality monitoring, etc. The extended functions can be realized to improve system management, including the life cycle and operation management, and the equipment monitoring.

V. DEVELOPMENT TRENDS OF IWAPC

Based on the Synchronized Information Platform, the more advanced applications of IWAPC for system security can be implemented. These key technologies are the researching trends of IWAPC in the future, including Network Topology Analysis, Wide Area Backup Protection, Intelligent Reclosing, Wide Area Load Shedding, Wide Area Bus Transfer, Overload Cutoff & Load Transfer, Transmission Section Protection, Intelligent System Splitting and Dynamic Stability Control, as shown in Fig. 6.

A. Network Topology Analysis & Application

Network topology analysis is one of the functions of system protection. It is also the core of the energy management system of the power grid. The function of the network topology analysis is the analysis and judgment of the structure of the power grid based on the state of the breakers. That is, it can express the power grid connected by various devices as nodes—branch

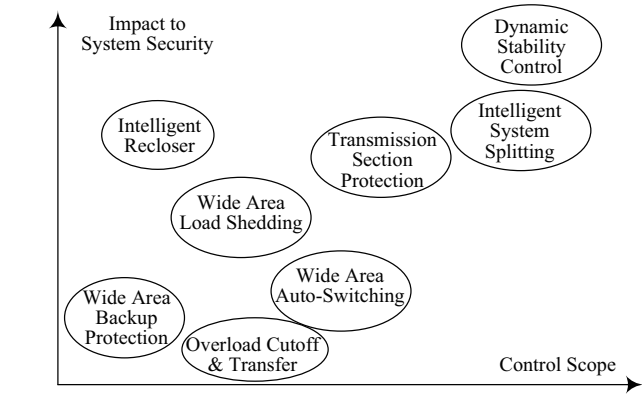


Fig. 6. Scope and impact of IWAPC key technologies.

models which can be used for power system analysis and calculation. And it can identify the isolated subsystems. The common methods of network topology analysis are the matrix method and the search method. Its reliability and rapidity directly impact on the performance of the system protection. Mastering the current operation mode and topological structure timely and correctly can lay the groundwork of the network frame for the realization of system protection.

It is the basis of the short-circuit calculation, state estimation, load flow calculation, fault location, isolation and power supply recovery, network reconfiguration, and so on. It can fully realize the complete consideration, and maximize the consumption renewable energy sources safely and reliably. It can adapt the characteristics of two-way flow which is generated by the grid connection of renewable energy sources.

B. Wide Area Self-adaptive Backup Protection

In the foreseeable future, the communication systems will

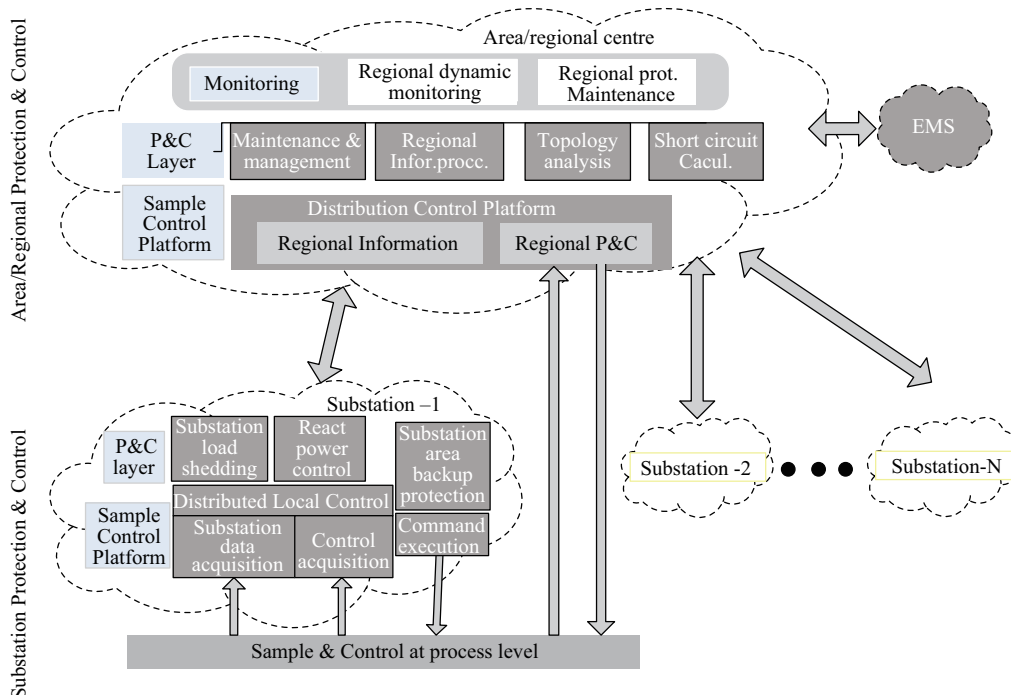


Fig. 5. Structure of distributed power cloud.

be developing rapidly and creating stability on the power backbone network. Therefore, the multi-terminal current differential relay can be utilized to improve the performance of a complicated grid. Based on the network topology analysis application, the protection region of the current differential relay can be extended to the wide area, as shown in Fig. 7. Thus, the new extended current differential relay will be configured as a wide area self-adaptive backup protection, with self-adapting performance and without sacrificing speed. However, based on the financial situation, the capacity of the communication system on the distribution network may not be adequate enough to merge the sample values. Based on the direction, overcurrent and distance, along with the intermediate information of the local relay, the wide area backup protection is able to analyze the fault location in different connection topology structures, without the need for a hierarchical setting requirement. The type and connection relationship of each primary piece of equipment determines how the intermediate information is used to calculate a fault integrated value in the wide area backup protection. The fault equipment has a different integrated value with the others. This method has good adaptability to the setting and cooperation of traditional backup protection.

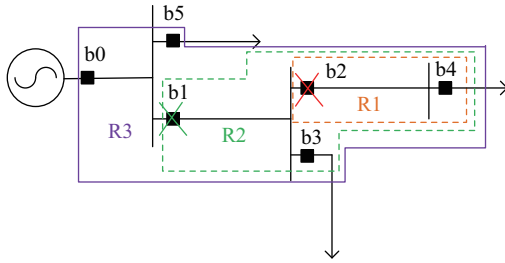


Fig. 7. Extended region of the current differential relay.

C. Wide Area Intelligent Reclosing

Wide area intelligent reclosing can judge and identify the fault type to be either transient or permanent by using the wide area information, and then calculate the transient energy of the system using a numerical integration program for the optimal reclosing time. When reclosing on a permanent fault, the imbalance energy of this fault can be offset, and the dynamic stability of the system will be improved. Moreover, for the optimal reclosing time calculated by the transient energy, the influence of the distance of the fault, the transmission power and the protect action time can be ignored. When the optimal reclosing time is used on a single-phase reclosing, the transient stability limit of the corresponding fault can be improved by about 5%–11%. And for the three-phase reclosing, this number will be larger.

D. Wide Area Load Shedding

The conventional load shedding device is designed separately with the degree of transient voltage or frequency drop, based on a fixed setting. Wide area load shedding is a co-operative scheme for transient voltage stability and frequency stability, providing a dynamic load shedding plan. By considering the regional grid frequency, the voltage offset of the

load buses, the change of the active power and reactive power, the scheme employs an index to allocate load curtailments at critical load buses considering the impact of the fault, and assesses adaptively the value of the load shedding on-line. This novel index, considering the change of the load reactive power and the degree of transient voltage drop, and deriving from the first-order model of the induction motor, can represent the variation of the equivalent load susceptance, and can measure the degree of the transient power system instability of different load models. Compared with the classical load shedding, this scheme can avoid the excessive or insufficient load, and guarantee power system stability more effectively.

E. Wide Area Auto-switching

Based on the synchronized high speed communication network, the speed and reliability of sampling and information sharing are greatly improved, which makes wide area auto-switching realizable. The measurement information of multiple substations in the region is acquired by the regional P&C synchronous data platform. Considering the Comprehensive information from multiple substations, and the fault situation and network structure, the integrated wide area or regional protection and control system develops wide area auto-switching control strategies, and sends the control instructions. It realizes the switching of the standby power supply in multiple substations. Before this action, the integrated wide area or regional protection and control system first carries out the security check of the action logic to prevent the overload caused by auto-switching. The wide area auto-switching flow chart is shown in Fig. 8.

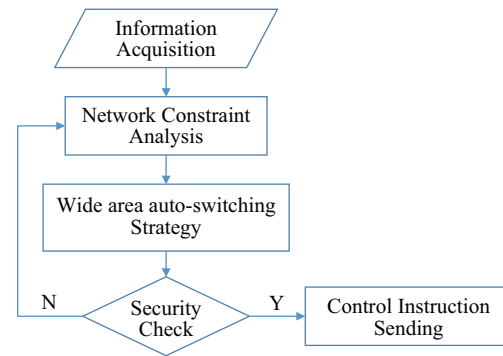


Fig. 8. Wide area auto-switching flow chart.

Traditional auto-switching is based on local information and can only control the standby power supply inside the station. And it is unable to consider the effect of the area network. Wide area auto-switching can recognize the standby power switch between different substations and avoid overload of the area after the device is put into operation. Therefore, it improves the power supply reliability, and shortens the recovery time.

F. Overload Cutoff & Transfer

After the fault protection action, in order to prevent the normal line or equipment overload operation, the traditional overload cutoff device can disconnect the electrical unit which

is directly linked to its substation, so that it realizes load removal for the whole line or station. However, it has a high probability of over-cut or under-cut, because the overload criterion, the setting value and control strategy of the device are simple. In addition, the device lacks self-adaption capability, therefore, a malfunction could happen when changing the operation method.

The overload cutoff, based on the wide information, requires the collection of electrical information which is from the key node of each substation in the protection area. The integrated system protection synthetically analyzes the overload situation and system power flow in the area, intensively optimizes the cutoff overload and control strategy, and sends commands to the multiple local overload cutoff device, so that it realizes the distributed overload cutoff. Moreover, integrated system protection can transfer the load through the operation method or network structure modification. Consequently, the overload can be reduced or avoided. This protection can avoid overcut and malfunction, improve self-adaption capability, decrease the power cut off range and it effectively solves the contradiction between the safety operation and power supply reliability.

G. Transmission Section Protection

When overloaded, the existing protections only try to eliminate the overload line without considering the impact of flow transferring. And cascading tripped by transferred overload may occur in the grid. Transmission section protection is of great importance to prevent cascading overload trips. This security protection can depend upon pre-fault network topology and pre-fault power flow of the wide area, to maintain its integrity and transmission capacity. The implement condition and key technology allows for the online capture of transmission sections, real-time prediction of cascading overload and real-time emergency control to avoid a cascading trip. This method ensures that the power flow of the overload branch won't arise, and the normal branch won't overload, so the control strategy is available to quickly eliminate overload.

H. Intelligent System Splitting

The traditional out-of-step splitting relay is generally mounted on the distribute location tripped predetermined transmission line. The out-of-step generator cluster exchanges power via the transmission section, but not through a line. With the enlargement of the power grid, including multiple transmission lines and various out-of-step modes, the traditional out-of-step splitting relay has proved to be unsuitable. Based on wide area real-time power flow, the intelligent system splitting selects the minimum cut-set of the power sections as the out-of-step splitting spots. Because of the optimization match between the source and load of the power system, the subsystems can be synchronous and balanceable after splitting. Therefore, intelligent system splitting can reduce power loss and improve grid self-healing capability.

I. Dynamic Stability Control

Dynamic stability control with the wide area measurement system and phase measurement unit, can first instantly collect

the power angle and the angular velocity of the generator, then obtain the geometric features of the trajectory by a real-time calculate, and at the same time predict the change of the trajectory, then evaluate the transient instability of the system with the criterion of the geometric features. Finally, a closed-loop control strategy for dynamic stability will be proposed based on the emergency control system. The advantage of the dynamic stability control with geometric features of the trajectory is that it can calculate and forecast the dynamic stability of the grid in real time, and transfer real-time closed-loop control measures to the system. When large disturbances happen, the dynamic stability control system could stop the loss of synchronism between grids, so as to improve the self-healing capacity of the electricity power system.

VI. CONCLUSION

The system protection scheme of IWAPC is presented in this paper. Based on the hierarchical structure, the integrated wide area protection and control is able to implement protection and control at the bay, substation and regional levels. The real-time synchronized communication platform is designed to support regional protection and control in transmission and distribution networks. By integrating the latest developments in protection techniques and advanced power system security control, it cannot only achieve fast protection, but also realize security control of the regional power grid. The essential benefits are as follows:

- 1) to eliminate the information island by wide area information sharing;
- 2) to improve performance of the local backup protection;
- 3) to implement perfect coordination between the local protection and system control;
- 4) to support dynamic system security protection instead of static system control;
- 5) to improve security and reliability of the power grid.

It offers a potential to integrate the "three defense lines" into a unified protection and control system, which can effectively improve the reliability and security of the regional power system.

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