Integrated Wide Area Protection and Control for Power Grid Security

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***Abstract*—the traditional "three defense lines" for power system is based on local information and static protection & control strategy, which is not suitable to modern large-scale power system. In order to improve the security of UHV hybrid power grid, 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 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 power grid.**

***Index Terms*—wide-area protection & control, digital substation, power grid security control, system protection**

I. INTRODUCTION

The new technologies, such as large-scale renewable generation, AC/DC hybrid transmission, ultra-high voltage transmission, flexible AC transmission, multi-terminal HVDC, have been applied rapidly in modern power grid, 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 difficulty for protection. However, the present protection and control are still at the level for the individual elements, which is difficult to achieve system-level fault self-healing, automatic optimization and adjustment. Meanwhile, the existing element protection with the limitations of local information, cannot meet requirements of modern power grid. The backup protection requires further optimization to improve the reliability, selectivity and sensitivity.

The progress in modern technology stimulates the development in power system protection [1]. Particularly, the application of novel communication technique and the utilization of global positioning system (GPS) in power system protection marked the start of new development 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 network [3-4]. The wide area protection has been presented focusing on power system control [5]. In these years, the development of signal processing and communication technologies for relaying protection platforms provided a new opportunity to revisit the 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 practical development and application 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 power system 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], detection and damping of inter-area oscillations [13]. But, the most important and challengeable applications 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 [15][16], which include wide area protection equipment and system at different levels. There were also important developments in recent years in the integrated wide area protection [17] and the integrated protection and control [18]. The Wide-Area Differential Protection [19] and Wide Area Backup Protection [20] are proposed to improve the performance of existing protection. The research and engineering practice of wide area protection and control system are discussed to bring out several urgent problems for improving wide area protection technology [21].

By analyzing the limitation of traditional "three defense lines", the Integrated Wide Area Protection & Control (IWAPC), or the System Protection in brief for integrating the "three defense lines", is 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 details with an aim to develop an optimal coordination mechanism between the 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 three lines of defense for power system protection and control, but also improve security of power grid.

II. TRADITIONAL "THREE DEFENSE LINES" THEORY AND ITS LIMITATIONS

The "three defense lines" has been widely used in power system. 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 shielding;*

3) *The third line the separation relay after loss of synchronism followed by the frequency and the voltage emergency control.*

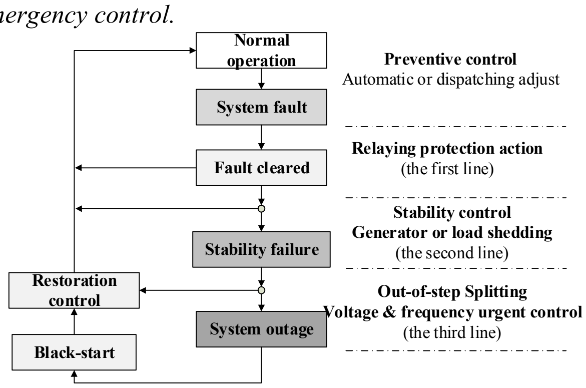

Fig.1 'three defense lines' for power grid security

The "three defense lines" of power grid stability is designed to prevent the electric power system from unstable status 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 of fault component using 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 system collapse by using frequency and voltage emergency control device when serious damage is occurred.

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

III. INTEGRATED WIDE AREA PROTECTION & CONTROL

The basic architecture of IWAPC system is shown in Fig.2. There have been fast development in both power transmission and distribution networks in recent years, for example FACTS and HVDC in transmission system, and distributed generations and micro-grid in distribution system, etc. These new developments cause the modern power grid more complicated characteristics than conventional systems. Therefore, the existing protection is not effective anymore. The IWAPC system is necessary to future power system [23]. The IWAPC system mainly consists 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 synchronisation 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 "three defense lines" in this paper provides significant development to traditional wide-area protection. It cannot only implement security control based on wide-area information, but also integrate coordinative functionalities of different levels including protection, automation and system stability control in substation and protection & control center.

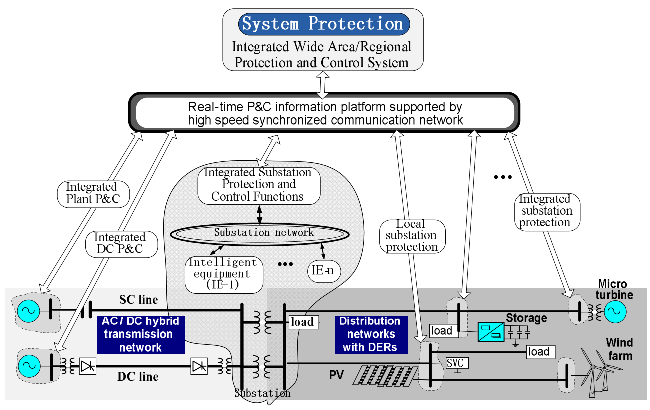

Fig.2 Architecture of Integrated Wide Area P&C

The IWAPC can be extended to achieve the integration of relaying protection, security control and substation automation of power system, including the functionalities of regional protection, control and advanced application. The IWAPC proposed in this paper is totally different from the traditional "three defense line". The functionalities of IWAPC are located to different level 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 local level, which are implemented in “All-in-one” IEDs in digital substation. 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 wide area protection level, including voltage and frequency control, etc.

1） ”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 merging unit, intelligent terminal and local protection for single bay. The structure of “all-in-one” device is shown in Fig. 3. There are different interfaces for conventional electro-magnetic transformer and unconventional as merging unit. 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 Generic Object Oriented Substation Event (GOOSE). Some functionalities of protection & control, which belongs to bay logic level, are implemented in “all-in-one” device to improve reliability of protection & control system in case of communication failure. Only protection and control based on single bay information can be configured in “all-in-one” device, such as line protection based on current differential relay, distance relay and overcurrent relay. The “all-in-one” devices should be installed nearby primary equipment.

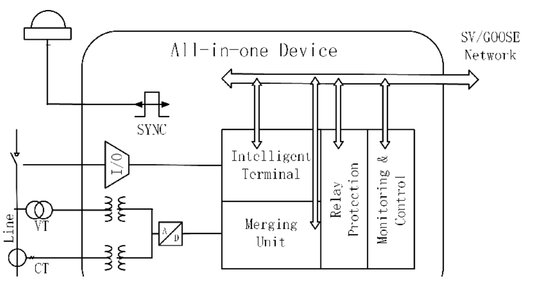

Fig.3 Structure of “all-in-one” IED in the local level

According to principle of IWAPC, the existing functionalities of local protection are optimized. Only main protections based on local fault information are reserved in local ”All-in-one” IEDs. The standby backup protection & control are available only in condition of substation protection failure. The optimal functionalities of transmission line protection are shown in Table 1 and 2 for example. Table 1 shows the functionalities of traditional local protection; Table 2 shows 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

Table 1 the functionalities of traditional local protection

P & C	**Function**
Current Diff	1Ph 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
	Directional under power protection
Voltage protection	Two step under-voltage protection
	Two step overvoltage protection
	Two step residual overvoltage protection
	Voltage differential protection
	Loss of voltage check
Frequency protection	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

Table 2 the optimal functionalities of local IED

2）Substation protection & control in the substation level

The substation protection & control does not only integrate the backup protection of transmission line, bus and transformer, but also implement functions of substation control, including auto 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 control are realized by entire substation information. The stage overcurrent protection, breaker failure protection and dead zone protection in the conventional protection system are substituted by extended current differential protection.

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

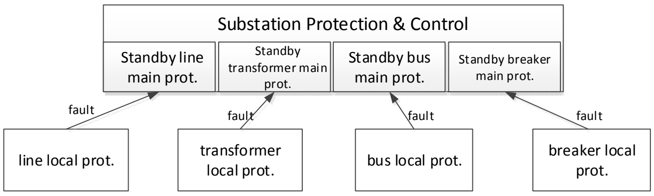

Fig.4 The substitution of local main protection by substation protection

3) 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 substation and regional protection & control centre, such as low-frequency and low-voltage load shedding, voltage and frequency control, automatic bus transfer. The function of transmission cross section safety P&C can be realized by IWAPC based on sharing information of 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 comparing 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 power system is based on the Synchronous Digital Hierarchy (SDH) communication network, which is a multi-service communication platform [23]. The advantages of SDH are the 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 mostly meet the demands for network communications in real time and dependability. Based on multi-protocol label switch(MPLS) traffic engineering, the specificity problem in wide-area protection communication system can be solved, including the quality of service(QoS) requirements and the path selection of traffic balancing [24].

But the Packet Transport Network (PTN) is more suitable to be used for wide area protection and control. Comparing to SDH, PTN is based Packet-switched technology to realise 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

Substation installs a wide range of electrical equipment, with complex design and difficult to maintain. With the continuous improvement in power system automation and the intelligence level, the system network have been expanding, so as the 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, complex communication protocols, forming information islands. This result in the measurement data and protection control mechanism cannot be shared, which restricts the information integration. The protection and control of smart grid has requirements to deal with and demands for new situation of the application; further improve the information platform capabilities for the future rapid development provide key technologies; making information platform system more open.

The real time synchronized information platform accurately collects wide area information [25]. In the platform, the sets of data that need to be transferred and their transferring speed depend on the application, 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 the time synchronization. On the other hand, the information is stored in a hierarchical manner instead of centralized one, which is comprised with the hierarchical protection and control system.

The introduction of advanced computing technology to build synchronized information platform for wide area protection and control, build a panoramic operation and maintenance data collection network, provide a standardized interface to the terminal device, to form 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, break the barriers between protection and control systems at different substation 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, shown in Fig.5. These functions based on regional sharing information include 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, the equipment monitoring.

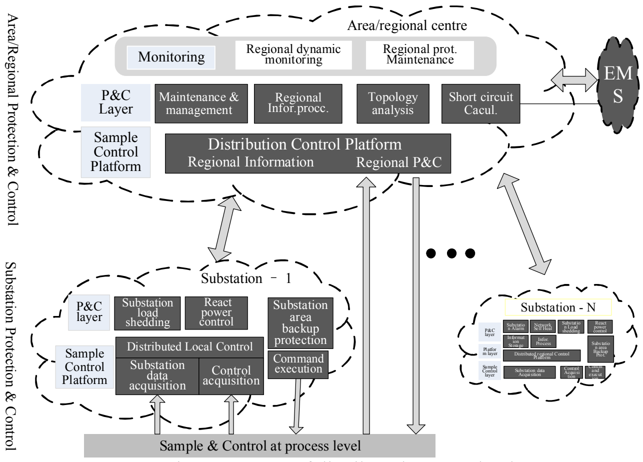

Fig.5 Structure of distributed power cloud

V. DEVELOPMENT TRENDS OF IWAPC

Based on 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, shown in Fig.6.

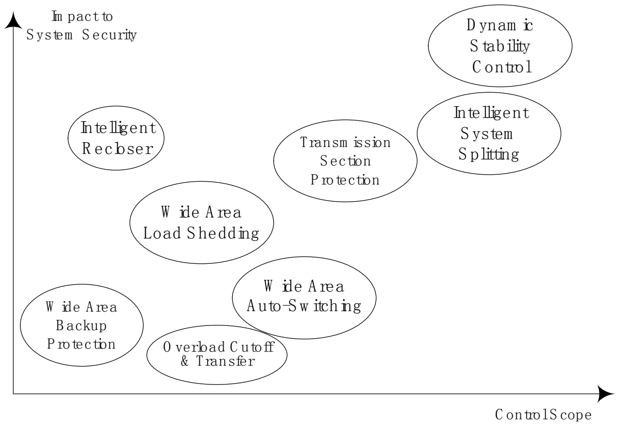

Fig.6 Scope and impact of IWAPC key technologies

A. Network topology analysis & application

Network topology analysis is one of the functions of system protection. It is also the core of energy management system of power grid. The function of the network topology analysis is the analysis and judgment of the structure of power grid based on the state of breakers. That is, it can express the power grid connected by various devices as nodes—branch 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 impact on the performance of system protection directly. Mastering the current operation mode and topological structure timely and correctly can lay the ground of network frame for the realization of the system protection.

It is the basis of the hort-circuit calculation, state estimation, load flow calculation, fault location, isolation and power supply recovery, network reconfiguration, and so on. It can realize wholly consideration, and maximize the consumption renewable energy sources safely and reliably. It can adapt the character 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 system will be developing rapidly and stability on power backbone network. Therefore, the multi-terminal current differential relay can be utilized to improve the performance of complicated grid. Based on network topology analysis application, the protection region of the current differential relay can be extended to wide area, shown in Fig.7. Thus, the new extended current differential relay will be figured as wide area self-adaptive backup protection, with self-adapting performance and without sacrificing speed. However, attributed to financial affair, the capacity of the communication system on distribution network may not be good enough to merge sample value. Based on direction, overcurrent and distance, which intermediate information of local relay, wide area backup protection can analyze the fault location in different connection topology structures, without hierarchical setting cooperation. The type and connection relationship of each primary equipment determines how intermediate information is used to calculate a fault integrated value in wide area backup protection. The fault equipment has a different integrated value with others. This method has a good adaptability to the setting and cooperation of traditional backup protection.

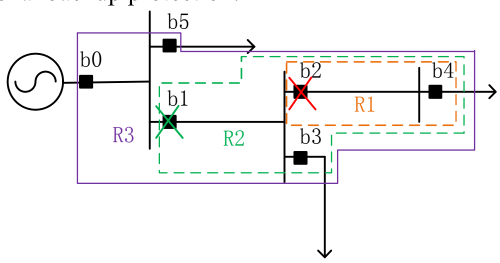

Fig.7 Extended region of the current differential relay

C. Wide-area intelligent reclosing

Wide area intelligent reclosing can judge and identify the fault type to be transient or permanent by using wide-area information, then calculate the transient energy of the system with 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 single-phase reclosing, the transient stability limit of the corresponding fault can be improved by about 5%-11%. And for three-phase reclosing, this number will be bigger.

D. Wide-area load shedding

The conventional load shedding device is designed separately with the degree of transient voltage or frequency drop, based on fixed setting. Wide area load shedding is a cooperative scheme for transient voltage stability and frequency stability, providing a dynamic load shedding plan. By considering the regional grid frequency, voltage offset of load buses, the change of the active power and reactive power, the scheme employs an index to allocate load curtailments at critical load buses with the impact of fault, and assesses adaptively the value of load shedding on-line. The novel index, such as consideration on the change of load reactive power and the degree of transient voltage drop, 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 synchronised high speed communication network, the speed and reliability of sampling and information sharing are greatly improved, which makes wide area auto-switching can be realized. The measurement information of multiple substations in the region is acquired by the regional P&C synchronous data platform. Comprehensive consideration of the information from multiple substations, fault situation and network structure, integrated wide area or regional protection and control system develops wide area auto-switching control strategies, and sends the control instruction. It realizes the switching of standby power supply in multiple substations. Before the action, integrated wide area or regional protection and control system carries on the security check of the action logic at first, to prevent the overload caused by auto-switching. Wide area auto-switching flow chart shown in Fig.8.

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 area network. Wide area auto-switching can realize the standby power switch between different substations, and avoid overload of the area after the device operation. Therefore, it improves the power supply reliability, and shortens the recovery time.

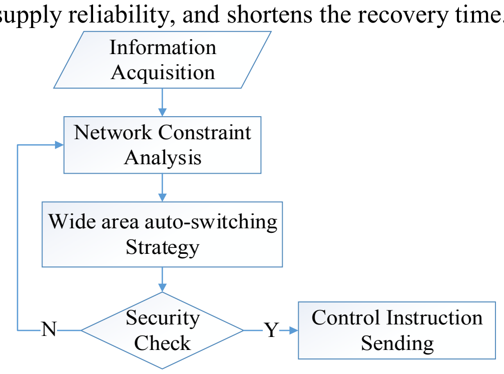

Fig.8 Wide area auto-switching flow chart

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 electrical unit which is directly linked to its substation, so that it realizes load removal for the whole line or station. However, it has 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 has lack of self-adaption capability, malfunction could happen when changing the operation method.

Overload cutoff based on the wide information need collect electrical information which is from key node of each substation in the protection area. Integrated system protection synthetically analysis overload situation and system power flow in the area, optimize intensively cutoff overload and control strategy, and send commends to multiple local overload cutoff device, so that it realizes distributed overload cutoff. Moreover, integrated system protection can transfer load through operation method or network structure modification. Consequently overload can be reduced or avoided. This protection can avoid overcut and malfunction, improve self-adaption capability, decrease 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 be occurred in 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 wide area, to maintain its integrality and transmission capacity. According to the implement condition and key technology, which are online capture of transmission section, real-time prediction of cascading overload and real-time emergency control to avoid cascading trip. The method ensures that the power flow of overload branch won't arise and normal branch won't overload, so the control strategy can availably and quickly eliminate overload.

H. Intelligent system splitting

The traditional out-of-step splitting rely is generally mounted on the distribute location tripped predetermined transmission line. Out-of-step generator cluster exchanges power via transmission section, but not a line. With the enlargement of the power grid, include multiple transmission lines and various out-of-step modes, the traditional out-of-step splitting relay has been unsuitable. Based on wide area real-time power flow, intelligent system splitting selects the minimum cut-set of power sections as out-of-step splitting spots. Because of optimization match between source and load of power system, 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 wide area measurement system and phase measurement unit, can first collect the power angle and the angular velocity of the generator instantly, then obtain the geometric features of the trajectory by real-time calculate, 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 trajectory can calculate and forecast the dynamic stability of the grid in real time, and take real-time closed-loop control measures to the system. When large disturbance happens, 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 implements protection and control at bay, substation and regional levels. The real-time synchronised communication platform is designed to support regional protection and control in transmission and distribution networks. By integrating the latest developments in protection techniques and the advanced power system security control, it cannot only achieve the fast protection, but also realize security control of regional power grid. The essential benefits are shown as follow:

1) to eliminate information island by wide-area inforamtion sharing;

2) to improve performance of local backup protection;

3) to implement perfect coordination between local protection and system control;

4) to support dynamic system security protection instead of static system control;

5) to improve security and reliability of power grid.

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

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