Protection and Control for Power Grid Security System

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Abstract:
This paper proposes the Integrated Wide Area Protection & Control (IWAPC) system to improve the security of large-scale power systems, specifically focusing on Ultra-High Voltage (UHV) hybrid power grids. The IWAPC utilizes synchronized high-speed communication and integrates the traditional "three defense lines" with existing wide area protection techniques. The system is structured into three levels: local bay level, substation integrated protection level, and wide area protection level. The core of the IWAPC is the wide area real-time protection and control information platform, based on a synchronized wide area communication network. Key technologies and development trends discussed in the paper 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. The IWAPC not only integrates power system protection and control, but also enhances the overall security and reliability of the power grid.

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

1. INTRODUCTION

The rapid adoption of new technologies in modern power grids, such as large-scale renewable generation, AC/DC hybrid transmission, ultra-high voltage transmission, flexible AC transmission, and multi-terminal HVDC, has led to increased complexity in transient behavior and a significant rise in the impact of partial failures. These developments pose a rapid and widespread threat to the network, presenting significant challenges for protection. However, the current protection and control systems are primarily focused on individual elements, making it difficult to achieve system-level fault self-healing, automatic optimization, and adjustments. Additionally, the existing element protection is limited by local information, failing to meet the evolving requirements for comprehensive network protection**.**

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

Advancements in modern technology have been instrumental in driving ongoing developments in power system protection [1]. The integration of novel communication techniques and the use of global positioning systems (GPS) in power system protection have paved the way for new innovations in recent times [2].
Several new techniques have been proposed, with a focus on providing protection for wide area power networks [3], [4]. The introduction of wide area protection has concentrated on power system control [5]. In recent years, advancements in signal processing and communication technologies have provided opportunities for revisiting centralized wide area protection.
Research on "Integrated Protection" [6] highlights the potential for developing new protection principles and schemes based on information from multiple substations and components. This has led to rapid development and practical applications in the area of substation protection [7]. Moreover, the emergence of information technology has sparked interest in utilizing cloud computing [8] and big data techniques to enhance the performance of power system protection and control.

The enhanced utilization of wide area measurements holds the potential to significantly elevate the operational and control aspects of wide area power systems. A diverse array of power system monitoring and control applications can be seamlessly integrated into the framework, aiming to augment system awareness and bolster reliability. These applications encompass a spectrum of functionalities, including refined state estimation leveraging a combination of Remote Terminal Unit (RTU) and Phasor Measurement Unit (PMU) measurements [9], [10], online estimation and validation of dynamic models [11], real-time congestion management, estimation of real-time stability [12], and the identification and suppression of inter-area oscillations [13]. Among these, the most pivotal and intricate undertaking is the establishment of real-time wide area stability detection and control, crucial for preemptively averting blackouts [14].

The dynamics, control mechanisms, models, and overarching system structures associated with Wide Area Protection have been subject to comprehensive discussion [15], [16], spanning a range of protective equipment and systems at varying hierarchical levels. Recent years have witnessed notable advancements in the realm of integrated wide area protection [17] and the fusion of protection and control functionalities [18]. Noteworthy propositions include Wide Area Differential Protection [19] and Wide Area Backup Protection [20], strategically devised to enhance the efficacy of existing protective measures. A detailed exploration of wide area protection and control systems in both research and engineering domains underscores critical challenges and prompts the pursuit of avenues for refining wide area protection technology [21].

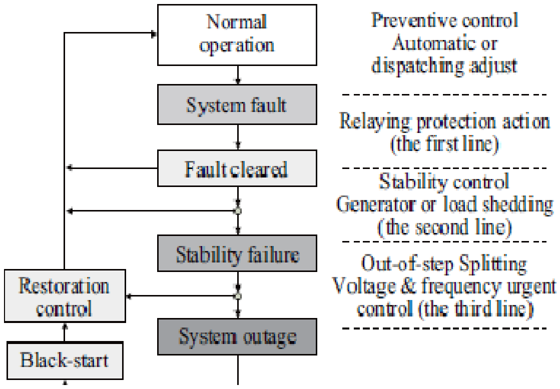
Through an examination of the limitations posed by conventional "three defense lines," the concept of Integrated Wide Area Protection & Control (IWAPC), also referred to as System Protection in a succinct context, has been brought forth. This multi-tiered concept comprises three distinct levels: the local bay level, the substation integrated protection level, and the wide area protection level. An intricate breakdown of the integrated functionalities is provided with a paramount objective of cultivating an optimal coordination framework spanning these different tiers. The paper elucidates essential technologies and emerging research trajectories, 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. The proposed framework not only harmonizes the three protective lines governing power system safeguarding and control but also augments the overarching security paradigm of the power grid.

II. TRADITIONAL"THREE DEFENSE LINES" THEORY ANDITS LIMITATIONS

The concept of the "three defense lines" has gained widespread application within power systems, serving as a comprehensive security defense system [22].

The initial line revolves around the protection relay system.
The second line encompasses stability and security control, incorporating actions like generator rejection and load shielding.
The third line involves the separation relay, triggered post-loss of synchronization, followed by frequency and voltage emergency control.

The purpose of the "three defense lines" in power grid stability is to preempt the electric power system from entering an unstable state, as depicted in Figure 1. The primary defense line operates as the most efficient approach, ensuring transient stability by promptly eliminating fault components through relay protection devices. The second line safeguards power system stability during significant disturbances, leveraging stability control devices, generator tripping, and load shedding.



The third layer of defense functions to uphold power equilibrium within the isolated power system following partitioning, thereby mitigating the risk of accidents culminating in system collapse. This is achieved through the utilization of frequency and voltage emergency control mechanisms in response to severe damage instances.

The traditional application of the "three defense lines" in power systems, founded upon localized information and static protection and control strategies, has become inadequate for modern power systems. This framework's limitations include the formation of information islands stemming from segregated stability control systems, a lack of synergy between protection and control mechanisms for diverse devices, and the fixed configuration of protection and control settings. These aspects no longer align with the evolving security requisites of contemporary power systems.

III. INTEGRATED WIDE AREA PROTECTION & CONTROL

The fundamental structure of an Integrated Wide Area Protection & Control (IWAPC) system is visually represented in Figure 2. Recent years have witnessed rapid advancements in both power transmission and distribution networks, such as the integration of Flexible AC Transmission Systems (FACTS) and High Voltage Direct Current (HVDC) systems in transmission, as well as the emergence of distributed generation and micro-grids in distribution networks. These innovations have led to heightened complexity in the modern power grid compared to conventional systems, rendering existing protection methodologies less effective. Consequently, the implementation of the IWAPC system becomes imperative for the future of power systems [23]. Notably, certain integrated protection strategies based on transient information have been introduced for distributed generations and micro-grids in distribution systems [24], [25], with their realization being underpinned by the IWAPC framework.

The IWAPC system is primarily structured around three tiers of equipment: "all-in-one" Intelligent Electronic Devices (IEDs) at the local bay level, integrated substation protection at the substation level, and wide area protection and control at the network-wide level. An essential component of the IWAPC is the comprehensive wide area synchronization communication network, encompassing both the substation communication network and the overarching integrated wide area communication network.

The innovative IWAPC system, as presented in this paper, brings about a significant advancement over traditional wide area protection methods. It goes beyond the mere implementation of security control predicated on wide area information and also integrates coordinated functionalities across various levels, encompassing protection, automation, and system stability control at both substation and protection & control centers. The scope of the IWAPC can be expanded to encompass the integration of relay protection, security control, and substation automation in power systems, inclusive of regional protection, control, and advanced applications. Crucially, the IWAPC concept proposed here diverges markedly from the traditional "three defense lines." The distribution of functionalities within the IWAPC is contingent upon the information gathering and sharing regions. Functions related to information acquisition and primary protection grounded in local bay information are situated at the local level, executed through "All-in-one" IEDs within digital substations. Substation protection and control, encompassing backup protection and substation control founded on substation data, are situated at the substation level, encompassing features such as automatic bus transfer, circuit breaker failure protection, and load shedding. Additionally, functionalities predicated on regional information are executed at the wide area protection level, including tasks like voltage and frequency control, among others.

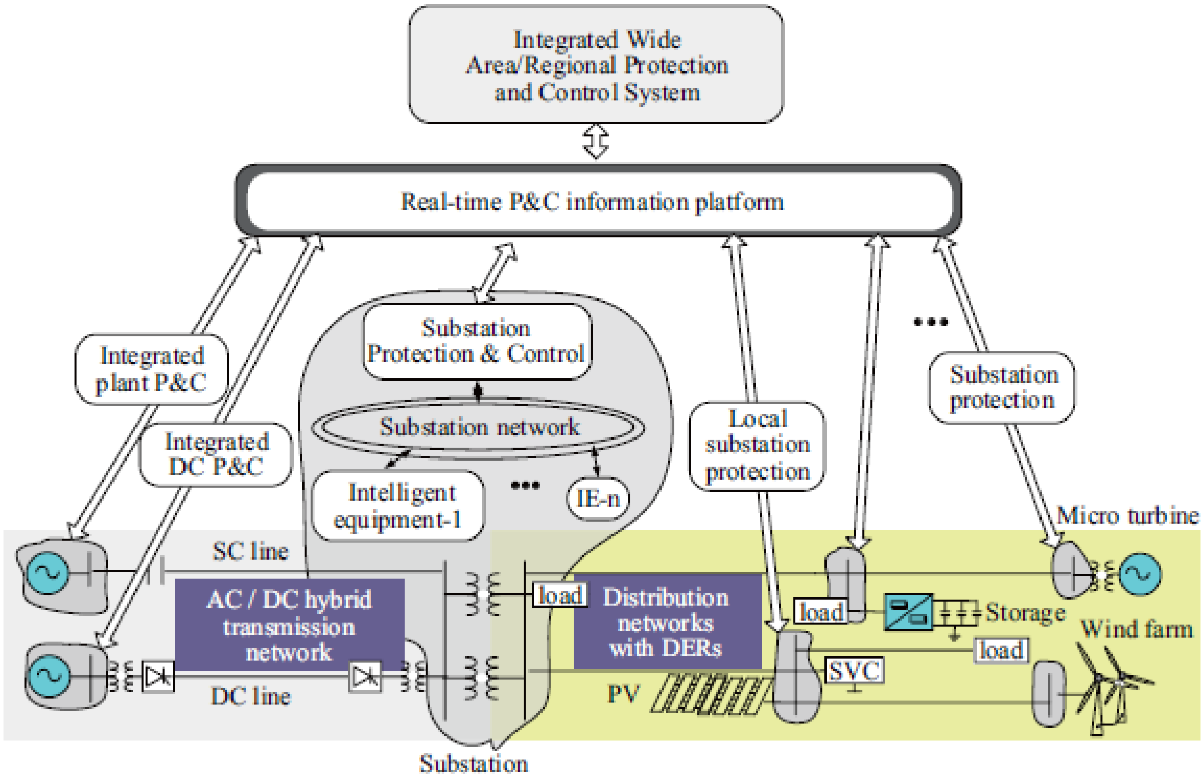


Fig. 2. Architecture of Integrated Wide Area P&C.

A. "All-in-one" IED in the Local Level

The cornerstone of IWAPC lies within the "All-in-one" Intelligent Electronic Device (IED) situated at the local level, as visualized in Figure 2. This innovation introduces the concept of an "all-in-one" device that seamlessly amalgamates the functions of a merging unit, intelligent terminal, and local protection into a single bay. The schematic representation of the "all-in-one" device's structure is depicted in Figure 3. Diverse interfaces cater to both conventional electromagnetic transformers and unconventional components such as merging units. The digital monitoring and control of breakers and switches are achieved, and local fault information serves as the basis for digital protections retained within local "All-in-one" IEDs. Standby backup protection and controls are only activated when there is a substation protection failure. Notably, optimal functionalities for transmission line protection are showcased in Table I and Table II, with Table I outlining traditional local protection functionalities and Table II spotlighting the optimal features of the local IED.

The "all-in-one" device boasts support for Sample Value (SV) communication in accordance with IEC61850-9-2, as well as the integration of Generic Object Oriented Substation Event (GOOSE) protocols. To enhance the reliability of the protection and control system in the face of communication breakdowns, select protection and control functionalities, categorized under bay logic level, are embedded within "all-in-one" devices. However, configuration within a "all-in-one" device is confined to protection and control based solely on single bay information. Instances include line protection contingent on the current differential relay, distance relay, and overcurrent relay. The strategic placement of "all-in-one" devices in proximity to primary equipment is recommended.

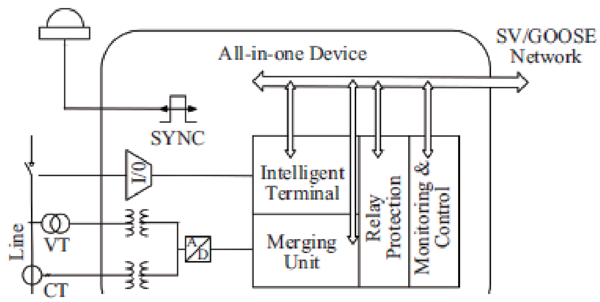


Fig. 3. Structure of "all-in-one" IED in the local level.

In line with the tenets of IWAPC, the functionalities of local protection are refined to align with optimized strategies. Within local "All-in-one" IEDs, exclusively principal protections reliant on local fault data are upheld. Standby backup protection and controls come into play solely when a substation protection failure scenario unfolds. For illustrative purposes, the enhanced functionalities of transmission line protection are outlined in both Table I and Table II. Table I outlines the functions associated with traditional local protection, while Table II details the advanced functionalities inherent to the local IED configuration.

TABLE I

THE FUNCTIONALITIES OF TRADITIONAL LOCAL PROTECTION

P & C	Function
Current Different	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

B. Substation Protection & Control in the Substation Level

The substation protection and control system not only amalgamates the backup protection for transmission lines, buses, and transformers but also encompasses various substation control functions. These functions encompass a range of actions, including automatic reclosing, automatic bus transfer, circuit breaker failure protection, load shedding in response to low frequency and low voltage conditions, overload inter-tripping, and more. The integrated substation backup protection and safety automatic controls draw on the entirety of substation information to operate effectively. Conventional protection system components like stage over current protection, breaker failure protection, and dead zone protection are supplanted by the extended current differential protection.

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

To bolster the reliability of the primary protection, the functions performed by the local IED are substituted by the standby functionalities of the substation protection level in cases where local IEDs experience failure or require maintenance. This approach ensures a seamless transition to the substation protection level's standby functions, as depicted in Figure 4. This substitution scheme proves highly beneficial, eliminating the need for redundant arrangements while maintaining optimal functionality.

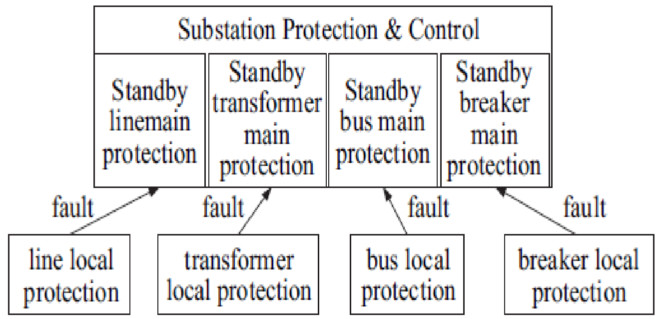


Fig. 4. The substitution of local main protection by substation protection.

C. Integrated Wide Area Protection and Control

The amalgamated wide area protection and control framework encompasses a synthesis of backup protection and security control functionalities. Certain functions find applicability at both the substation and the regional protection and control centers, examples being low-frequency and low-voltage load shedding, voltage and frequency control, as well as automatic bus transfer. Through information sharing across the regional power grid, the function of transmission cross section safety protection and control can be realized within the IWAPC paradigm, encompassing tasks like oscillation detection and out-of-step separation. Notably, the IWAPC introduces a harmonized fusion of protection and control, crafting an optimal integrated system that surpasses the traditional protection setup. This coherent system showcases the capability to orchestrate regional protection and control seamlessly, consequently yielding substantial enhancements to power system protection and operation.

IV.SYNCHRONIZED COMMUNICATION PLATFORM

A. Communication Network Based on PTN

The fundamental underpinning of the IWAPC system relies on a high-speed communication network. Currently, power system communication networks are constructed using the Synchronous Digital Hierarchy (SDH), a versatile multi-service communication platform [26]. SDH boasts advantages like heightened efficiency, minimal latency, and superior reliability. However, it also brings forth several challenges, encompassing inflexibility and limited data service-bearing efficiency. An upgraded SDH optical fiber self-healing ring network frequently suffices for real-time and dependable network communications. By leveraging Multi-Protocol Label Switching (MPLS) traffic engineering, the specific challenges within the wide area protection communication system, such as quality of service (QoS) requirements and path selection for traffic balancing, can be effectively addressed [27].

Nevertheless, the Packet Transport Network (PTN) proves more suitable for wide area protection and control. In contrast to SDH, PTN relies on packet-switched technology for statistical multiplexing and efficient packet service transmission. This transition enhances bandwidth flexibility and delivers superior operation, service quality, and administration. The integration of the wide area protection and control system relies on synchronized timing based on IEEE-1588 technology.

Maintaining synchronized information poses challenges. With the continuous advancement of power system automation and intelligence, the network expands, leading to a vast volume of protection and control information. Each piece of information, collected and stored by diverse devices across separate systems, results in poor interoperability, complex communication protocols, and information islands. Consequently, measurement data and protection control mechanisms remain inaccessible, constraining information integration. The evolving smart grid's protection and control mandates adaptations for novel applications, thus necessitating enhanced information platform capabilities. A more open information platform system emerges as a critical solution.

A real-time synchronized information platform adeptly collects wide area information [28]. In this platform, data sets and their transfer speeds are tailored to specific applications; slower for contingency analysis, near real-time for monitoring, real-time for control, and high-speed for wide area protection, particularly for time synchronization.

Information is hierarchically stored instead of centralized, comprising the hierarchical protection and control system.

Advanced computing technology facilitates the construction of a synchronized information platform for wide area protection and control, along with a comprehensive operation and maintenance data collection network. This involves providing standardized interfaces to terminal devices for resource sharing, flexibility, interactivity, openness, and orderliness in the information platform. In essence, advanced computing technologies culminate in the establishment of a distributed, collaborative, intelligent information platform, streamlining terminal data collection equipment and bridging gaps between protection and control systems at diverse substations through the meticulously designed synchronized information platform.

Built upon the synchronized communication platform, a distributed information system is devised to support Integrated Wide Area Protection & Control, as depicted in Figure 5. These functions, underpinned by regional information sharing, encompass wide area fault line selection, fault location, power quality monitoring, and more. Expanded functionalities extend to system management improvements, encompassing equipment lifecycle and operation management, as well as equipment monitoring.

B. Synchronized Information Platform

A substation hosts an extensive array of intricate electrical equipment, often characterized by complex designs and challenging maintenance requirements. As the power system continuously advances in automation and intelligence, the network's expansion results in a substantial influx of information within the realm of protection and control. However, each piece of data is collected and stored by distinct devices across separate systems, leading to poor interoperability, complex communication protocols, and the formation of isolated information clusters. This situation hinders the sharing of measurement data and protection control mechanisms, ultimately impeding comprehensive information integration. The dynamic landscape of the smart grid necessitates adaptive strategies to address new application scenarios, further reinforcing the importance of enhancing information platform capabilities to foster future rapid development and the evolution towards a more open information platform system.

The real-time synchronized information platform excels in accurately amassing wide area information [28]. Within this platform, the selection of data sets for transfer and their respective transmission speeds are tailored to specific applications. For instance, a gradual pace is suitable for contingency analysis, near-real-time suffices for monitoring, and instantaneous delivery is indispensable for control. The demands of wide area protection, especially in time synchronization, warrant high-speed transfers. Counterintuitively, information is hierarchically stored, deviating from the conventional centralized approach. This hierarchical structure is comprised of the hierarchical protection and control system.

Introducing advanced computing technology paves the way for establishing a synchronized information platform for wide area protection and control, which encompasses the creation of a panoramic operation and maintenance data collection network. A standardized interface is extended to terminal devices, fostering resource sharing, flexibility, interactivity, openness, and organization within the information platform. In essence, the deployment of advanced computing technologies facilitates the construction of a distributed, collaborative, and intelligent information platform, streamlining terminal data collection equipment and dismantling barriers between protection and control systems across different substations through the ingeniously designed synchronized information platform.

Based upon the synchronized communication platform, a distributed information system is meticulously designed to empower Integrated Wide Area Protection & Control, as delineated in Figure 5. These functions, grounded in regional information sharing, encompass various tasks like wide area fault line selection, fault location determination, and power quality monitoring. The potential expansion of these functionalities can contribute to enhanced system management, spanning the lifecycle of equipment, operational aspects, and equipment monitoring.

V. Development Trends of IWAPC

Drawing upon the foundation of the Synchronized Information Platform, the implementation of more sophisticated applications of IWAPC aimed at enhancing system security becomes feasible. These pivotal technologies constitute the focal points of IWAPC's future research endeavors, encompassing evolving trends such as 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. These technologies pave the way for a robust and secure power system , as depicted in Figure 6.

A. Network Topology Analysis & Application

Network topology analysis serves as a crucial facet of system protection, encompassing its role as the central element within the power grid's energy management system. This function entails dissecting and evaluating the power grid's structure, a process hinging on the state of circuit breakers. Essentially, this analysis translates the power grid interconnections via various devices into a network of nodes and branch models, which in turn can be harnessed for power system analysis and computations. Moreover, this analysis can adeptly discern isolated subsystems. The two common techniques employed for network topology analysis include the matrix method and the search method. The reliability and swiftness of these approaches exert a direct impact on the efficacy of the system protection mechanisms. Proficiently grasping the ongoing operational mode and the prevailing topological structure in a timely and precise manner forms the bedrock for establishing the network framework necessary to actualize effective system protection strategies.

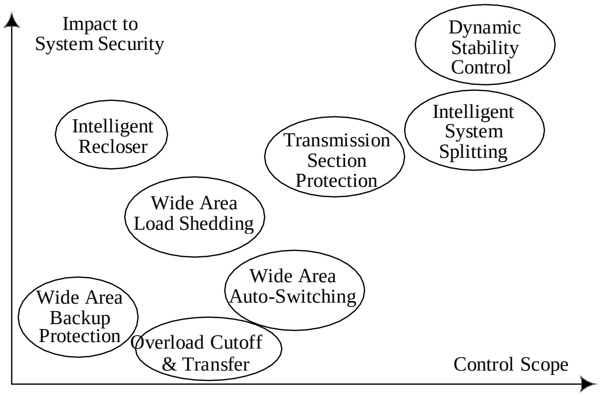


Fig. 6. Scope and impact of IWAPC key technologies.

Of equal significance, network topology analysis serves as the cornerstone for an array of functions, such as short-circuit calculations, state estimation, load flow computations, fault location, isolation, power restoration, network reconfiguration, and more. This comprehensive approach facilitates the secure and reliable optimization of renewable energy sources' utilization. It also adroitly adapts to the inherent characteristics of the bidirectional energy flow engendered by the integration of renewable energy sources into the power grid.

B. Wide Area Self-adaptive Backup Protection

In the foreseeable future, the evolution of communication systems is set to accelerate, introducing stability to the power backbone network. This progress opens avenues for leveraging the multi-terminal current differential relay to enhance the performance of intricate grids.

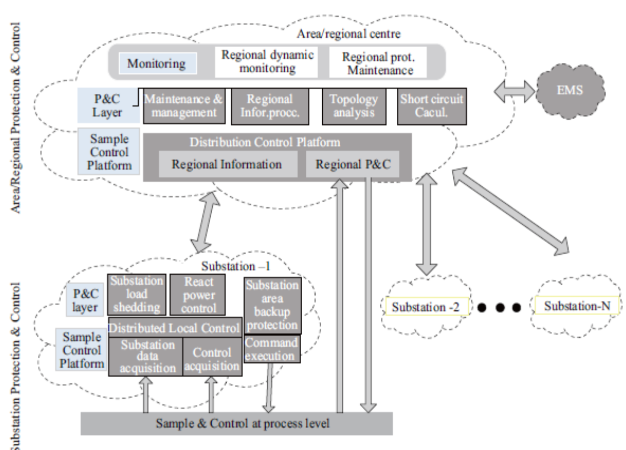


Fig. 5. Structure of distributed power cloud.

By leveraging applications in network topology analysis, the protective range of the current differential relay can be expanded to encompass wide areas, as depicted in Figure 7. Consequently, this novel extension of the current differential relay morphs into a wide area self-adaptive backup protection mechanism, boasting adaptable performance without compromising speed. It's worth noting that the communication system's capacity on the distribution network may pose limitations, hindering the merging of sample values due to financial constraints.

Incorporating factors like direction, overcurrent, distance, and the intermediary data from local relays, the wide area backup protection excels in fault location analysis across diverse connection topology structures. This prowess is achieved without necessitating hierarchical configuration requisites. The nature and interconnections of primary equipment dictate how the intermediary data is utilized to compute a fault's integrated value within the ambit of wide area backup protection. Unique faulted equipment yields distinctive integrated values compared to others. This methodology impeccably adapts to the traditional backup protection's setup and cooperative mechanisms, offering a versatile solution for various protection scenarios.

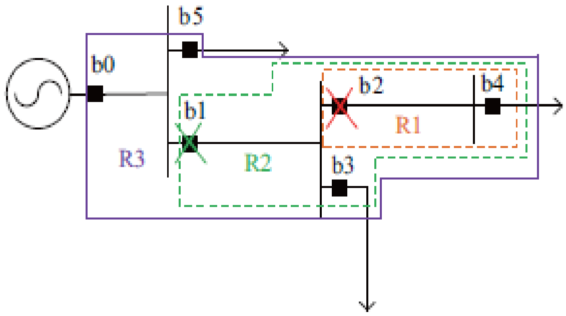


Fig. 5. Structure of distributed power cloud.

C. Wide Area Intelligent Reclosing

Wide area intelligent reclosing takes advantage of expansive information to accurately discern whether a fault is transient or permanent. It subsequently employs this determination to calculate the transient energy within the system via a numerical integration process, leading to the identification of the most suitable time for optimal reclosure. In situations where reclosure transpires on a permanent fault, the energy imbalance associated with the fault can be mitigated, yielding an enhancement in the system's dynamic stability. Notably, when the optimal reclosure time is computed based on transient energy considerations, factors like fault distance, transmission power, and protection action time can be conveniently disregarded.

Incorporating the optimal reclosure time derived from transient energy analysis yields tangible benefits, as it substantially mitigates the influence of fault distance, transmission power, and protection action time. When this optimal reclosure time is applied in scenarios involving single-phase reclosure, the transient stability limit of the relevant fault can witness a notable improvement of approximately 5%–11%. This enhancement is even more pronounced in the case of three-phase reclosure, showcasing the efficacy of this approach in bolstering system stability.

D. Wide Area Load Shedding

The conventional load shedding mechanism is typically devised as a separate entity, responsive solely to transient voltage or frequency drops, relying on static settings. In contrast, wide area load shedding emerges as a collaborative strategy catering to both transient voltage and frequency stability, offering a dynamic load shedding blueprint. This novel approach factors in various parameters, such as regional grid frequency, voltage deviations at load buses, changes in active and reactive power, to devise a load curtailment strategy at critical load buses, accounting for fault impacts. Furthermore, this scheme dynamically evaluates the online value of load shedding, ensuring adaptability in response to changing conditions.

A pioneering index, derived from the first-order model of the induction motor and encompassing considerations like load reactive power changes and transient voltage drop levels, plays a pivotal role. This index adeptly encapsulates variations in equivalent load susceptance and quantifies the extent of transient power system instability across diverse load models. In contrast to traditional load shedding methodologies, this scheme effectively circumvents scenarios of excessive or inadequate load shedding, significantly enhancing the power system's overall stability and ensuring its uninterrupted operation.

E. Wide Area Auto-switching

Leveraging the capabilities of the synchronized high-speed communication network, the efficiency and dependability of both sampling and information sharing experience substantial enhancements, rendering wide area auto-switching a feasible reality. The measurement data emanating from multiple substations within a given region is gathered via the synchronized regional Protection and Control (P&C) data platform. This comprehensive dataset, coupled with fault scenarios and network configuration insights, serves as the basis for devising wide area auto-switching control strategies within the integrated regional protection and control system. Subsequently, these control instructions are dispatched to facilitate the seamless transition of standby power supplies across multiple substations.

Prior to initiating such actions, the integrated regional protection and control system executes a security check of the proposed action logic. This precautionary measure is instrumental in averting potential overloads stemming from auto-switching operations. The orchestrated sequence of wide area auto-switching operations is illustrated in the flow chart depicted in Figure 8.

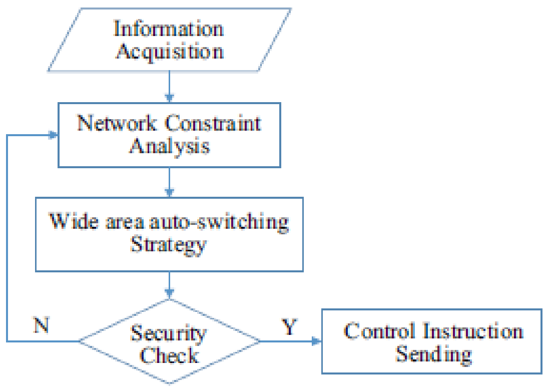


Fig. 8. Wide area auto-switching flow chart.

Conventional auto-switching mechanisms rely solely on local information and are limited to managing standby power within individual substations, lacking the capacity to account for broader network implications. In contrast, wide area auto-switching transcends these limitations by identifying and managing standby power switches across multiple substations, thereby circumventing the risk of area-wide overloads following device activation. This paradigm shift enhances power supply reliability and expedites system recovery, underscoring its pivotal role in fortifying the power grid's robustness.

F. Overload Cutoff & Transfer

Conventional auto-switching mechanisms rely solely on local information and are limited to managing standby power within individual substations, lacking the capacity to account for broader network implications. In contrast, wide area auto-switching transcends these limitations by identifying and managing standby power switches across multiple substations, thereby circumventing the risk of area-wide overloads following device activation. This paradigm shift enhances power supply reliability and expedites system recovery, underscoring its pivotal role in fortifying the power grid's robustness.

G. Transmission Section Protection

In situations of overload, existing protective measures often focus solely on eliminating the overloaded line without accounting for the potential consequences of power flow redistribution. This omission can lead to cascading tripping in the grid, underscoring the critical significance of transmission section protection in preempting such scenarios. This form of security protection leverages the pre-fault network topology and pre-fault power flow across the wider area to sustain the integrity and transmission capacity of the network.The successful execution of this protection hinges on its ability to capture transmission sections in real-time and to predict cascading overload events. Armed with these insights, real-time emergency control strategies can be promptly deployed to avert the onset of cascading trips. By ensuring that power flow doesn't surge in overloaded branches and that normal branches remain free from overloads, this methodology facilitates the rapid elimination of overloads while maintaining grid stability.

H. Intelligent System Splitting

Traditionally, the out-of-step splitting relay is typically positioned at predetermined locations on distributed transmission lines. In cases involving out-of-step generator clusters, power exchange transpires through transmission sections rather than individual lines. As the power grid expands to encompass multiple transmission lines and diverse out-of-step scenarios, the conventional out-of-step splitting relay's efficacy diminishes. In response, an intelligent system splitting approach is adopted, grounded in wide area real-time power flow analysis.

This advanced strategy employs intelligent algorithms to identify the optimal out-of-step splitting points, selecting the minimal cut-set of power sections. This choice aligns with the optimized match between the power system's source and load. The result is synchronous and balanced subsystems post-splitting. Consequently, intelligent system splitting not only curbs power loss but also enhances the grid's self-healing ability, fostering improved overall grid stability.

I. Dynamic Stability Control

Dynamic stability control, integrated with the wide area measurement system and phase measurement unit, facilitates instantaneous acquisition of generator power angle and angular velocity. This information is then employed to compute the geometric attributes of the trajectory in real-time, enabling concurrent trajectory change predictions. Subsequently, the transient instability of the system is assessed using geometric feature criteria. This assessment lays the foundation for the formulation of a closed-loop control strategy for dynamic stability, integrated within the emergency control system.

The inherent advantage of this dynamic stability control approach, grounded in trajectory geometric features, lies in its capacity to perform real-time calculations and forecasts of grid dynamic stability. Moreover, it enables the swift deployment of real-time closed-loop control measures into the system. This mechanism is particularly potent in instances of significant disturbances, as the dynamic stability control system can intervene to avert grid synchronism loss. Consequently, this proactive intervention enhances the electricity power system's self-healing capability.

VI. CONCLUSION

The system protection framework of IWAPC is expounded upon in this paper. Grounded in its hierarchical structure, the integrated wide area protection and control system operates seamlessly across bay, substation, and regional levels. This is facilitated by a real-time synchronized communication platform designed to empower regional protection and control across both transmission and distribution networks. By amalgamating cutting-edge protection techniques and advanced power system security control strategies, this system delivers not only swift protection responses but also comprehensive security control over the regional power grid.

The advantages bestowed by this approach are manifold:

- Eradicating information isolation through wide area information sharing.
- Enhancing the efficacy of local backup protection measures.
- Enabling seamless coordination between local protection and system control functionalities.
- Enabling dynamic system security protection as opposed to static system control.
- Enhancing the overall security and reliability of the power grid.
- Furthermore, this approach harbors the potential to harmonize the "three defense lines" into a unified protection and control system. This integration holds the promise of substantively elevating the reliability and security of regional power systems.

REFERENCES

- G. D. Rockefeller, “Fault protection with a digital computer,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS–88, no. 4, pp. 438–461, Apr. 1969.
- Z. Q. Bo, F. Jiang, Z. Chen, X. Z. Dong, G. Weller, and M. A. Redfern, “Transient based protection for power transmission systems,” in *Proceedings of 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings*, Jan. 2000.
- Z. Q. Bo, J. A. S. B. Jayasinge, R. K. Aggarwal, et al, “A new scheme for monitoring and protection of power transmission system based on global positioning system,” in *Proceedings of the 31st University PowerEngineering Conference*, Crete, Greece, 1996, pp. 21–24.
- Z. Q. Bo, G. Weller, T. Lomas, and M. A. Redfern, “Positional protection of transmission systems using global positioning system,” *IEEE Transactions on Power Delivery*, vol. 15, no. 4, pp. 1163–1168, Oct. 2000.
- B. Ingelsson, P. O. Lindstrom, D. Karlsson, G. Runvik, and J. O. Sjodin, “Wide-area protection against voltage collapse,” *IEEE Computer Applications in Power*, vol. 10, no. 4, pp. 30–35, Oct. 1997.
- Z. Q. Bo, L. Wang, F. Q. Zhou, K. M. Luo, M. Han, W. J. Yin,and J. Y. Liu, “Substation cloud computing for secondary auxiliary equipment,” in *Proceedings of 2014 International Conference on PowerSystem Technology*, Chengdu, China, Oct. 2014,
- Y. Guo, W. C. Wu, B. M. Zhang, and H. B. Sun, “A distributed state estimation method for power systems incorporating linear and nonlinear models,” *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 608–616, Jan. 2015.
- W. U. Rahman, M. Ali, A. Ullah, H. U. Rahman, M. Iqbal, H. Ahmad, A. Zeb, Z. Ali, M. A. Shahzad, and B. Taj, “Advancementin wide area monitoring protection and control using PMU’s model in MATLAB/SIMULINK,” *Smart Grid and Renewable Energy*, vol. 3, no.4, pp. 294–307, 2012.
- H. X. Qin and B. Yao, “Research and engineering practice of wide area protection and control systems,” *Journal of International Council on Electrical Engineering*, vol. 3, no. 2, pp. 169–173, Apr. 2013.
- Y. G. Zhang, J. F. Zhang, J. Ma, and Z. P. Wang, “Fault detection basedon hierarchical cluster analysis in wide area backup protection system,” *Energy and Power Engineering*, vol. 1, no. 1, pp. 21–27, Aug. 2009.
- W. Wang, J. Chen, R. Yu, and L. P. Wang, “Case of coordination of three lines of defense which guarantee grid stable operation,” *Electric Power*, vol. 44, no. 10, pp. 16–20, Oct. 2011.
- Z. Q. Bo, Q. P. Wang, L. Wang, F. Q. Zhou, S. M. Ge, and B. M.Zhang, “Architecture design for integrated wide area protection andcontrol systems,” *Journal of Power and Energy Engineering*, vol. 3,no. 4, pp. 412–416, Apr. 2015.
- X. P. Xiong, J. C. Tan, and X. N. Lin,"“Routing algorithm for communi-cation system in wide-area protection based on MPLS,” *Transactions of China Electrotechnical Society*, vol. 28, no. 7, pp. 257–263, Jun. 2013.
- Z. Q. Bo, S. M. Ge, Q. P. Wang, L. Wang, F. Q. Zhou, X. Liu, and Z. F. Fan, “Integrated wide area protection and control systems based on advanced communication network,” in *Proceedings of 2015 International Conference on Industrial Technology and Management Science*, Tianjin, China, Mar. 2015.
- W. J. Yin, D. Yuan, J. G. Li, R. Y. Han, J. F. Di, and Y. Wei, “Researchon wide-area protection system based on SDH network,” *Power System Protection and Control*, vol. 39, no. 5, pp. 120–123, 127, Mar. 2011.
- Z. Q. Bo, J. H. He, and X. Z. Dong, “Integrated protection of power network,” *Relay*, vol. 33, no. 14, pp. 33–41, 2005.
- H. L. Gao, Y. Q. Liu, J. J. Su, D. M. Cui, J. Liu, and M. J. Xiang, “New type of substation-area backup protection for intelligent substation,”*Power System Protection and Control*, vol. 41, no. 2, pp. 32–38, Jan. 2013.

- Z. Q. Bo, L. Wang, F. Q. Zhou, K. M. Luo, M. Han, W. J. Yin,and J. Y. Liu, “Substation cloud computing for secondary auxiliary equipment,” in *Proceedings of 2014 International Conference on PowerSystem Technology*, Chengdu, China, Oct. 2014,
- Y. Guo, W. C. Wu, B. M. Zhang, and H. B. Sun, “A distributed state estimation method for power systems incorporating linear and nonlinearmodels,” *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 608–616, Jan. 2015.
- W. U. Rahman, M. Ali, A. Ullah, H. U. Rahman, M. Iqbal, H. Ahmad, A. Zeb, Z. Ali, M. A. Shahzad, and B. Taj, “Advancementin wide area monitoring protection and control using PMU’s model in MATLAB/SIMULINK,” *Smart Grid and Renewable Energy*, vol. 3, no.4, pp. 294–307, 2012.

- R. Z. Chen, W. C. Wu, H. B. Sun, and B. M. Zhang, “A two-level onlineparameter identification approach,” in *Proceedings of 2013 IEEE Power& Energy Society General Meeting*, Vancouver, BC, Canada, Jul. 2013, pp. 21–25.
- M. S. Liu, B. M. Zhang, L. Z. Yao, M. Han, H. B. Sun, and W. C.Wu, “PMU based voltage stability analysis for transmission corridors,” in *Proceedings of the 3rd International Conference on Electric Util-ity Deregulation and Restructuring and Power Technologies*, Nanjing, China, Apr. 2008,
- J. B. He, C. Lu, X. C. Wu, J. T. Wu, and T. S. Bi, “Design and experiment of heuristic adaptive HVDC supplementary damping controller based ononline Prony analysis,” in *Proceedings of 2007 IEEE Power EngineeringSociety General Meeting*, Jun. 2007.
- W. C. Wu, B. M. Zhang, H. B. Sun, and Y. Zhang, “Development and application of on-line dynamic security early warning and preventive control system in China,” in *Proceedings of the IEEE PES General Meeting*, Jul. 2010.
- Y. S. Xue, X. Lei, F Xue, F. S. Wen, Z. Y. Dong, and G. Ledwich, “Review on wide area protection of electric power systems,” *High Voltage Engineering*, vol. 38, no. 3, pp. 513–520, Mar. 2012

