Research on Key Technology of Primary Protection System in Intelligent Substation

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Abstract. The smart substation in this paper is a model. Through the research of its primary system, the project construction scale and design scope, electrical main wiring, short-circuit current and main equipment selection, insulation coordination and overvoltage protection, cable facilities, power distribution equipment, etc. To conduct research. Analyze application status detection, fully optimize design, and improve operation and maintenance management. Combining the online monitoring and sequential control operation of the intelligent substation, the research of the secondary protection design scheme is carried out. It analyses the system dispatch automation, integrated power supply system, system and station communication, secondary equipment cabinet and layout, component protection and automatic equipment, etc., focusing on online monitoring, sequential control operation and operation and maintenance management. With the maturity of online monitoring technology, the realization of sequence control operation technology and the application of optical fibre network in real-time systems, the safety level and operation and maintenance management of smart substations will surely be better improved.

Keywords: Smart substation, primary system, secondary protection design scheme, key technology.

1. Introduction
With the rapid growth of power demand, the development of the digital economy, strict environmental supervision and the adjustment of energy policies in various countries, the relationship between the power grid and the power market and customers is getting closer. Customers' requirements for power quality are gradually increasing, and distributed energy sources continue to increase. Traditional power networks have been unable to meet these development requirements. In order to meet the requirements of energy saving, environmental protection, high efficiency, reliability, stability and sustainable development of power supply, the construction of smart grid is imperative. As an important node in the smart grid, smart substations are responsible for the real-time collection and release of substation equipment status and grid operation data and information. At the same time, they support real-time grid control, intelligent adjustment and various advanced applications, and realize substation and dispatching, adjacent Collaborative interaction among substations, power supplies, and users [1]. Smart substations not only provide a data analysis basis for the safe and stable operation of
the power grid, but also provide important technical support for the future smart grid to achieve its high efficiency and self-healing functions. This paper studies the intelligent primary equipment and secondary protection, including intelligent transformers, high-voltage switchgear, condition maintenance technology, online monitoring technology, sequential control operation technology, etc. Compared with conventional substations, the biggest advancement of smart substations lies in the secondary system communication, which is mainly reflected in the secondary system's architecture, data transmission methods, data collection methods, and internal communication protocols. According to the actual engineering design and operation and maintenance management analysis at the present stage, the research conclusions are drawn, which will provide important reference and reference value for the design of smart substations in the future.

2. Intelligent Substation Relay Protection System Architecture

Smart substations generally adopt a three-layer (process layer, bay layer, station control layer) and two networks (process layer bus, station control layer bus) structure mode. Different devices in and between layers transmit data through high-speed Ethernet. And use MMS, GOOSE, SV and other messages to achieve information exchange [2]. The equipment in the station adopts IEEE 1588 station-wide centralized network time synchronization. Figure 1 is a typical 110 KV intelligent substation protection system architecture. After the electrical quantity information collected by the electronic transformer is processed by the merging unit, on the one hand, it is directly sent to the intelligent protection equipment of this bay, and on the other hand, it is sent to the SV network through the bay switch; correspondingly, the intelligent protection equipment can directly receive this bay. Information about the merging unit ("direct acquisition") can also be obtained through the SV network ("net acquisition"). Through the analysis and processing of the information, the trip command is transmitted to the intelligent terminal via the GOOSE network ("network jump") or directly through the optical fibre ("direct jump") to control whether the circuit breaker trips.

![Figure 1. Typical 110KV intelligent substation protection architecture](Image)

In the "direct acquisition" mode, the relevant specifications require that the protection system can independently complete the protection function without relying on external time synchronization. Therefore, it is not necessary to consider the influence of the synchronous clock source in the reliability assessment process; for the "net acquisition" mode, due to the delay in data transmission, the influence of the synchronous clock source needs to be taken into account in the reliability assessment.
2.1. Distribution network reliability assessment model
The power system is formed by multiple and large number of components connected in a certain order. Due to the certain difference in the number of components and the connection mode, the functions to be realized are still very different. Components are connected in series in the line from the power supply to the load point to form a system. Once there is a problem with the operating state of a component in the system, or a node in the line fails, it will make the entire power system normal power supply error occurred. Only when all the constituent elements of the entire system operate normally, the series system can realize normal operation. The specific series equivalent diagram of components is shown in Figure 2.

![Figure 2. Equivalent elements in series](image)

As shown in the figure above, the series system relies on two components. The state of the above two components will not be affected by the state of each other. Therefore, the reliability index of the series system can be obtained by calculation. The specific calculation is as follows:

\[ \lambda_s = \lambda_1 \lambda_2 (r_1 + r_2) \]

\[ r_i = \frac{r_1 r_2}{r_1 + r_2} \]

In the above expression, \( \lambda_s \) represents the failure rate of the series system, times/year; \( r \) represents the average power outage time, hours/time.

2.2. Reliability index
Reliability indicators generally require specific data parameters to feed back the reliability level, and of course the distribution network is no exception. The establishment of a scientific distribution network reliability index evaluation system can provide a more practical and effective feedback on the reliability level of the entire distribution network. In addition, for some reliability problems that cannot meet the requirements, purposeful improvements are needed to guide the optimization and improvement of the distribution network more effectively [3].

2.2.1. Reliability index of load point. By analysing and summarizing related references and combining current engineering examples, the reliability indicators of the nodes can be divided into average failure rate, failure repair time and average outage time. details as follows:

(1) The average failure rate of the load node is marked with \( \lambda_i \). The average failure rate \( \lambda_i \) of the load node refers to the number of failures that occur due to component failures in the distribution network within the specified counting period during the one-year operation of node I, which causes the node to lose power. Specifically expressed by the following formula:

\[ \lambda_i = \sum_{j=1}^{n} \lambda_j \]

In the above formula, there are: \( n \) represents the sum of the number of components that may cause power failure to load node I; \( j \) represents the number of the component; \( \lambda_j \) represents the failure rate of the component.
2. The average outage time of the load node is marked with $U_i$. The average power outage time of the load node in a limited time period is measured in hours, as expressed by the following formula:

$$U_i = \sum_{j=1}^{n} \lambda_j r_j$$

(4)

In the above formula, $r_j$ represents the average power failure time of component $j$, in hours.

3. The average duration of power outage at the load node is represented by $r_i$. The average power outage duration of a load node refers to the time required to restore power after a power outage. It can be expressed by the ratio of the length of the power outage of the load node to the average number of outages, as shown in the following formula:

$$r_i = \frac{U_i}{\lambda_i} = \frac{\sum_{j=1}^{n} \lambda_j r_j}{\sum_{j=1}^{n} \lambda_j}$$

(5)

In the above formula, $N_i$ represents the statistical value of the total number of electricity consumption units of load node $i$; $\lambda_i$ represents the probability of a power outage of load node $i$ in a given time period; $U_i$ represents the average of the total power outage time of load node $i$ in one year value.

2.2.2. System reliability index. The reliability index of the load node is mainly to reflect the evaluation of the power supply capacity of each load node in a certain time period or counting period. Of course, load nodes are only mutually independent and mutually influencing components in the distribution network structure, and their individual parameter indicators cannot reflect the reliability level of the entire distribution network. But through these parameters, analysis and calculation can get the final system reliability parameter level. The reliability index evaluation of the distribution network system is expressed by the following formula:

1. The average frequency of power outages in the distribution network, represented by the English symbol SAIFI. This index represents the sum of the number of power outages that occurred in each power consumption system in the distribution network system in a predetermined counting period in each year. To calculate this index, you must first comprehensively count the number of users in the distribution network, and then analyse the number of power outages in each user in the counting cycle, and then add the number of power outages of all users to calculate the total number of users. Obtain the index (times/user year).

$$SAIFI = \frac{\sum N_i \lambda_i}{\sum N_i}$$

(6)

2. The average duration of power outages in the distribution network, represented by the English symbol SAIDI. This indicator represents the average power outage time of each user in the distribution network in a given counting period. To calculate this index, it is necessary to count the total number of users in the distribution network. The time for each user to have outages in a given counting period. The ratio of the total length of outage time of all users in the distribution network to the total number of users is the index the value of (hour/user year).
(3) The average frequency of power outages in the distribution network is represented by CAIFI in English. This indicator represents the average number of power outages in a given counting period for users affected by power outages. The premise of calculating this indicator is to list the number of power outages of all users in the distribution network and the number of users affected by the wave of power outages. Furthermore, the ratio of the sum of the number of power outages of each user to the sum of the number of users affected by the power outage is used to represent the above index value (times/user*year).

\[ \text{CAIFI} = \frac{\sum N_i}{\sum N} \]  

(4) The average duration of power outages for users in the distribution network, represented by the English symbol CAIDI. This indicator represents the average time that each user in the distribution network is affected by a power outage in a given counting period. The prerequisite for calculating this index is to list the cumulative length of time for each user in the distribution network to have power outages in a predetermined counting period, and to list the number of power outages for all users, and then get the ratio of the two. Indicates the indicator (hours/power outage users*years).

\[ \text{CAIDI} = \frac{\sum N_i}{\sum N} \]  

(5) Average power supply reliability rate. The English symbol represents ASAI. This indicator represents the actual power supply rate obtained by all users in the distribution network during the counting period. To calculate this indicator, we must first calculate the length of time to the user's actual supply of electricity and the theoretical length of time to apply the supply of electricity. This indicator is calculated in hours. In view of the fact that the user's power supply expectation is not simple continuous power supply, for this reason, a year is used as a cycle to calculate, in theory, the total power supply hours should be 8760 hours. The ratio of the actual power supply time to the theoretical power supply time can get the average power supply reliability rate (%).

\[ \text{ASAI} = \frac{8760 \sum N_i - \sum N_i}{8760 N} \times 100\% \]  

(6) The average power supply is not available, and the English symbol represents ASUI. This index represents the ratio of the actual power outage time to the theoretical power supply time in a given counting period for users of the distribution network. The prerequisite for calculating this index is to obtain the actual power outage of the user in a predetermined counting period, and theoretically apply the length of time to supply electric energy. This index is calculated in hours. In view of the fact that the user's power supply expectation is not simple continuous power supply, for this reason, a year is used as a cycle to calculate, in theory, the total power supply hours should be 8760 hours. The ratio of the two is the solution of the above index (%).

\[ \text{ASUI} = \frac{\sum N_i}{8760 N_i} \times 100\% \]  

(7) Insufficient battery indicator, the English symbol represents ENS. This indicator refers to the reduction in the amount of power supplied by users after a failure in the distribution network. The
calculation premise of this indicator is to obtain the average power outage probability and the power outage duration of each power consumption unit in the system in the counting period. After the two are multiplied, the value (degree) of insufficient power can be obtained.

\[ ENS = \sum L_U \]

(12)

(8) Insufficient average power indicator, the English symbol represents AENS. This indicator refers to the calculation of the lack of power supply. The total number of users in the distribution network is obtained, and the two values are divided to obtain the power outage of each user in the distribution network due to insufficient power supply. Loss of power supply (degrees/number of users in the distribution network)

\[ AENS = \frac{ENS}{\sum N_i} \]

(13)

In order to make the index evaluation more scientific and reasonable, the power outage time is more than five minutes. The above-mentioned users are all units and individuals with independent electric energy meters, and the statistical time length value is one year. However, power outages caused by force majeure such as natural disasters are not included. The system fault status caused by the failure of different components in the protection system is different: For information transmission components, such as OF and SW. When it fails, it will only cause data to be missing, and will not produce wrong data. Therefore, it will only lead to the refusal of protection but not the malfunction of protection; and the components involved in data processing and command execution, such as MU, IED, EU, etc. Once a failure occurs, it may either cause the protection to malfunction or cause the protection to refuse. Therefore, in the reliability analysis of the protection system, the refusal and maloperation of these components are considered separately in this paper. And consider that the probability of the occurrence of the two types of failures, each accounted for half of the total failure probability of the component, as shown in Table 1.

| Component name | Job probability | Probability of refusal | Probability of maloperation |
|----------------|-----------------|------------------------|-----------------------------|
| MU             | 0.99998164      | 0.00000918             | 0.00000918                  |
| IED            | 0.99998164      | 0.00000918             | 0.00000918                  |
| TS             | 0.99998164      | 0.00000918             | 0.00000918                  |
| SW             | 0.99994521      | 0.00005479             | /                           |
| EU             | 0.99998164      | 0.00000918             | 0.00000918                  |
| OF             | 0.99999726      | 0.00000274             | /                           |

3. The key technology of primary protection system

3.1. Hardware integration technology

The process of information collection and processing in traditional substations is completed by the cooperation of the central processing unit and peripheral chips or equipment. A large number of data calculation and logic analysis processes and the realization of some advanced application functions are concentrated in the central processing unit. The level of performance determines the speed and quality of various functions. The central processing unit used here can be DSP, ARM, or CPU. The disadvantage of this design is that on the one hand, the central processor itself has limited integrated resources, which cannot meet the increasing demand for real-time processing of information in smart substations, thus becoming a bottleneck in the development of smart substation technology; on the other hand, the processor itself integrates many other hardware resources are idle because they cannot
meet the needs of smart substations, resulting in a waste of resources. In addition, the deletion of the operating system in the embedded system is a very tedious task, and the complexity of the operating system also increases the difficulty of system testing and the probability of errors [4].

With the development of modern electronics, the emergence of hardware description language makes the design of hardware systems show the characteristics of modelling, integration and automation. These characteristics enable the hardware design to achieve a truly functional modular design, which can solidify certain fixed logic processing procedures inside the smart device, and convert the functions originally implemented by some software into hardware implementation. This design not only ensures the real-time, reliability and accuracy of logic processing, and solves the bottleneck problem in information transmission; it also saves the cost of hardware resources and improves the integration of equipment; in addition, the modular design is also convenient Maintenance, replacement and upgrade of smart devices. The application of hardware integration technology in smart substations will break the hardware design concept of traditional substation equipment, change the layout of substation hardware equipment, and open a new page in the design of substation hardware equipment.

3.2. Software component technology

The software system in the intelligent substation can not only realize traditional measurement and control, information management and other functions, but also integrate PMU (phasor measurement unit), wave recording and other functions to realize station state estimation, regional centralized control, online state monitoring, Advanced functions such as remote maintenance, power quality evaluation, and intelligent management, and can generate system engineering data according to project configuration files, and realize functions such as automatic reconstruction of substation systems and equipment system models. To achieve the above functions, the application of software component technology is essential.

Software component refers to a program body that has certain functions and can work independently or assembled with other components to coordinate work. The essence of software component technology is to combine and encapsulate a set of codes or classes at different granularities to complete one or more specific services of functions, and then provide users with interfaces. The core idea of component technology is dividing and conquer. Component technology improves the abstraction of the system to a higher level than object-oriented technology. Software reuse technology is an important means to realize component technology. How to extract reusable components and how to assemble into a system and achieve interoperability are key issues faced by component technology [5].

3.3. Protection and control technology of distributed power

The access of distributed power sources improves the flexibility, efficiency and safety of the smart grid, changes the characteristics of the unidirectional power flow of the power distribution system, and turns the traditional single-source radiation network into a multi-source network. This breaks the coordination relationship established between the protection devices in the smart substation, and the action behaviour and performance of the protection will be greatly affected. The research on protection algorithms for large-capacity distributed power sources connected to smart grids is also the key content of smart substation relay protection. Distributed energy, as an independent overall module, can be operated in an isolated grid or connected to the grid on a large power grid. The influence of distributed energy on the frequency, reactive power and voltage stability of the grid when it is connected to the system cannot be ignored [6]. Therefore, how to ensure that the relay protection system can respond to distributed power failures in a timely manner under any working conditions, and at the same time, the relay protection system also has the ability to quickly sense large grid failures and ensure protection Selectivity, rapidity, sensitivity and reliability are the difficult topics of intelligent substation relay protection.
4. Case analysis

4.1. Reliability index setting

According to the definition of intelligent substation in the DL/T 860 standard, intelligent substation is divided into process layer, bay layer and station control layer. High-speed Ethernet is used for data communication within each layer and between layers. The following analysis takes the 220 kV protection system model of a typical smart substation in Figure 3 as a calculation example.

![Figure 3. Typical 220 kV smart substation](image)

In the actual operation of the site, the corresponding reliability basic data can be determined according to the protection's incorrect action records, abnormal alarm information and failure cause analysis records. In this paper, the protection system self-check success rate $\eta$ is set to 90%. Refer to the existing data and combine the actual situation of the intelligent substation to set the protection system failure rate data as shown in Table 2 and Table 3.

| Table 2. Failure rate data 1 |
|-----------------------------|
| d1 | d2 | d3 | h1 | h2 | h3 | zw |
| 53.7 | 32.6 | 0.05 | 5.53 | 4.12 | 0.01 | 130.5 |

| Table 3. Failure rate data 2 |
|-----------------------------|
| tw_1 | tw_2 | tw_3 | tj_1 | tj_2 | tj_3 | zj |
| 4.523 | 785 | 137 | 364 | 587 | 13147.7 |

4.2. Analysis of maintenance requirements under different repair rates

The repair rate reflects the equipment maintenance level and overhaul efficiency. The following lists three groups of repair rate data to reflect the changes in protection reliability and maintenance
requirements with the repair rate. Each group of data is marked as the i-th (I=1,2,3) level, as shown in Table 4.

| Repair rate data |
|------------------|
| | μ₁₁ | μ₁₂ | μ₁₃ | μ₁₄ | μ₁₅ |
| Level 1 | 15.73 | 16.86 | 20.54 | 13.74 | 15.34 |
| Level 2 | 157.30 | 168.60 | 205.40 | 137.40 | 153.40 |

Substituting the data in Table 2 to Table 4 into the above formula can obtain the maintenance demand probability of the steady-state protection system, as shown in Table 5. It can be seen that as the repair rate increases, the protection system maintenance demand probability gradually decreases. If 0.7 is regarded as the probability threshold of $P_{cbrn}$ (that is, the protection system needs to be repaired when the value is greater than this value), the repair rate level is lower (first, Level 2), the protection system is necessary for maintenance. In order to improve reliability, the protection system should minimize maintenance time.

| Probability of protection system status |
|----------------------------------------|
| Repair rate | Protection system state probability | P(I) | P(II) | P(III) | P_{cbrn} |
| Level 1     | 0.0381 | 0.2135 | 0.7484 | 0.9619 |
| Level 2     | 0.2664 | 0.2103 | 0.5234 | 0.7336 |
| Level 3     | 0.6647 | 0.2047 | 0.1306 | 0.3353 |

4.3. The impact of changes in the success rate of self-inspection on maintenance requirements

Taking the calculation result of the third-level repair rate in section 4.2 as the initial state probability, the characteristics of the time-varying maintenance demand probability $P_{cbrn}$ can be obtained through the Markov model of the protection system. On this basis, changing the self-inspection success rate $\eta$ can further analyse the impact on the maintenance requirements of the protection system.

Figure 4 shows the change curve of the protection system maintenance demand probability within 30 days calculated according to the dynamic Markov probability analysis method. The success rate of
the self-inspection is reduced from 90% to 50% during the calculation. It can be seen that as the success rate of self-inspection decreases, the maintenance requirements of the protection system gradually increase. In addition, according to the changing trend of the curve, when the self-inspection success rate $\eta$ is 90%, the protection system under study needs to be overhauled at about 4000h. Based on the above analysis, it can be known that the protection system maintenance demand probability calculated in the article basically conforms to the operation of the device. Therefore, this index has a certain reference value for the protection device maintenance decision-making.

5. Conclusion
The relay protection online operation and maintenance system realizes the status monitoring and early warning of the status of the relay protection equipment and the secondary circuit of the smart substation, laying the foundation for the status monitoring and maintenance of the relay protection equipment. This article introduces the main functions of the operation and maintenance system, discusses the realization of key technologies such as related modelling, communication and architecture, and gives engineering application cases, which have reference significance for the further promotion and application of the operation and maintenance system.

References
[1] Nan, D. Wang, W., Mahfoud, R. J., Alhelou, H. H., & Zhang, L. Risk assessment of smart substation relay protection system based on markov model and risk transfer network. Energies, 13 (7), 15-19.
[2] Balakrishna, P. Rajagopal, K., & Swarup, K. S. Distribution automation analysis based on extended load data from ami systems integration. International Journal of Electrical Power & Energy Systems, 86 (3) (2017)154-162.
[3] Qu, T. Lei, S. P., Wang, Z. Z., Nie, D. X., Chen, X., & Huang, G. Q. Iot-based real-time production logistics synchronization system under smart cloud manufacturing. International Journal of Advanced Manufacturing Technology, 84(4) (2016) 147-164.
[4] Eduardo, C. Jaime, C., Martín Cristian, & Rubio Bartolomé. Smart winery: a real-time monitoring system for structural health and ullage in fino style wine casks. Sensors, 18(3) (2018) 803-814.
[5] Liu, Y. Gao, H., Gao, W., & Peng, F. Development of a substation-area backup protective relay for smart substation. IEEE Transactions on Smart Grid, 8(99) (2017) 2544-2553.
[6] Moreira, N. Molina, E. Lazaro, J., Jacob, E., & Astarloa, A. Cyber-security in substation automation systems. Renewable & Sustainable Energy Reviews, 54(2) (2016) 1552-1562.