Research on Intelligent Diagnosis Strategy of Secondary Device Abnormity in Smart Substation

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Abstract. With the high integration of smart substations, the traditional secondary cable in the conventional substation, which is unable to carry out online monitoring, has been replaced by the fiber-optic network with online monitoring function. The operation and maintenance personnel conduct the status of the secondary circuit through the communication messages in the network message analyzer. However, the rapid growth of information result in a series of issues, for example information is not intuitive and coverage of important information. As the consequence, it is difficult to quickly find the location and cause of fault. For the issue of abnormal diagnosis of secondary equipment of intelligent substation, this paper studies the operation and maintenance mode and physical modelling of the secondary system, visualization technology, on-line state evaluation technology and the fault location technology. On this basis, an intelligent diagnosis strategy for the secondary device of the smart substation is put forward. Furthermore, a fault diagnosis platform is developed to implement real time monitoring of secondary circuit and analyze abnormal situation to ensure the safe and reliable operation of smart substation.

1. Introduction
The smart substation adopts optical fiber instead of the traditional cables, and uses digital information to replace the analog information of the conventional substation resulting the traditional non on-line monitoring cables transferring into on-line monitoring network. The secondary system network and the new smart substation monitoring greatly improves the controllability of the secondary system in the smart substation, and provides powerful support for the fault diagnosis of the smart substation [1]. In the smart substation, the operation and maintenance personnel obtain the state of the secondary circuit by monitoring the communication message in the network message analyser instead of monitoring the analog quantity. Since the amount of information of the secondary system increases, the information is too much to be monitored and not intuitionistic leading to ignoring some important information. Therefore, it is difficult to find the fault location and the cause of the fault quickly [2]-[4].

Aiming at the needs and problems of the smart substation operation and maintenance, this paper studies the architecture of intelligent diagnosis system which includes the secondary system operation and maintenance mode, physical modeling of secondary system, visualization technology, online state assessment technology and fault location technology. Subsequently, the modelling specification of physical circuit is proposed, and the demonstration of the whole secondary circuit of the device is achieved. The “trend” and “loss” evaluation system based on the full message of the substation is then established. To evaluate the health status of the device, the multi-parameter information fusion analysis method is used. By introducing the method of fault location of the secondary circuit in the process layer, a data set of all possible fault points is obtained. Hence, the most likely fault point is obtained through demonstrating the state of the equipment related to the fault circuit.
This paper proposes an intelligent diagnosis strategy for secondary equipment of smart substation, and develops a diagnosis platform for the secondary device fault and abnormality of the smart substation. The proposed method can obtain the state of secondary circuit in real time and analyze the abnormal situation for safe and reliable operation of smart station.

2. The main problems of operation and maintenance of the secondary system of Smart substation

In the smart substation, the communication network has replaced the traditional secondary circuit, the digital signal takes the place of the traditional physical and electrical signals. Compared with the traditional substation, there are three problems in the smart substation.

Secondary systems profession deep fusion, physical circuit complexity increased. Relay protection sampling, calculation and outlet are Integrated in conventional substations, data information, protection objects and devices are bound together, and operation and maintenance are simple and convenient. The composition of the smart substation equipment has changed greatly, newly added the process layer, merging unit, intelligent terminal, network switch and so on, the amount of information has increased greatly, and the secondary systems are more complex [5]-[8]. It is not intuitive to replace the cable with the optical fiber in the secondary circuit. The equipment in the conventional substation is connected by cables, and the secondary circuit is intuitively visible. The smart substation uses optical cable instead of cable, and the secondary circuit becomes virtual circuit. All the configuration of the case and communication parameters are included in the SCD, and the SCD file can not directly reflect the secondary circuit, configuration information such as communication parameters, signal association and so on, which can cause great inconvenience to operation and maintenance [9]-[12]. The secondary circuit state assessment and fault diagnosis methods are lacking, fault points can not be found quickly.[13]

Compared with the traditional substation, the secondary system structure of the smart substation is more complex, the visibility of the secondary circuit is poor, the secondary circuit state evaluation and the fault diagnosis means are short. At present, when the smart substation has the fault, the operation and maintenance personnel dependence on the factory to deal with it, which seriously affects the progress of the fault treatment and affects the safety of the smart substation maintenance. Therefore, it is necessary to study the intelligent diagnosis of the secondary device abnormality in smart substations.

3. Research on intelligent diagnosis strategy of the secondary device abnormality in Smart substation

From the conventional substation to the smart substation, although the secondary circuit turns into a virtual circuit, it brings problems to operation and maintenance, but the information provided by the smart substation is more comprehensive, and the information between device and device can be fully interactive. Using appropriate technology and means, the operators can master the status of the device more accurately. The following four main problems are studied in depth: 1) physical circuit model expansion; 2) visual display; 3) online status assessment; 4) fault location.

3.1. Expansion modeling of physical secondary circuits in smart substations

Expansion modeling of physical secondary circuits in smart substations means the abstract modeling of the existing physical circuits and combination to the SCD file, then form the physical and logical panoramic model of the substation. The main technical points of expansion modeling of physical secondary circuits in smart substations include: the decoupling design of the physical circuit and the logic circuit, the designers can design the logical circuit configuration file and the physical circuit configuration file in parallel to improve the design efficiency. When designing drawings or debugging, the two configuration files can be corresponded with virtual reality to realize the integrated design and application of virtual reality. Secondary circuit panoramic model design flow is shown in Figure 1. The design process of the physical circuit includes: importing the IPCD files of different physical equipment of secondary systems into the SPCD file configuration module, completing the hierarchical construction and the real circuit configuration in the SPCD. The system software completes the cable
layout automatically according to the above information. After the information configuration is completed, the whole SPCD file is generated.

The design process of the logic circuit includes: the equipment manufacturer generate the intelligent electronic device capability description (ICD) file through the IED configuration tool. The design unit completes the SCD file design of the whole substation through the ICD file. The SCD file can show the communication parameters and the virtual connection of the secondary device in smart substations. The application of secondary physical circuit expansion modeling techniques can not only improve the efficiency of work, and also make operation and maintenance of the smart substation more conveniently, and because upgrade the traditional image management mode to the visualization mode, the operation and maintenance personnel will no longer rely on a large amount of drawings.

3.2. Visualization technology of smart substation secondary system

The visualization technology of smart substation secondary system means through analyzing the SCD file to match the SV, GOOSE and MMS messages which are obtained online, set up the mapping relationship between the physical connection of the optical cable and the logical link connection and the mapping relationship between the logical link and the secondary functional circuit, then through pattern mapping, the physical connection diagram, optical cable communication link diagram, relay protection principle and pressure plate diagram are automatically generated, achieve no "blind spot" online monitoring and self-diagnosis alarm, so as to realize the visual monitoring of the smart substation secondary system.

The innovation of the visualization technology is the use of core automatic search algorithm. In the analysis of the physical level, because the physical path is more complex and the fiber is more difficult to draw, the use of the core automatic search algorithm can solve this problem well. The core automatic search algorithm uses the Core element and the IntCore element in the SPCD file format as the entry point, extending the search on both sides, and finally searching for the devices on both sides. For example, when the A side is the device, how automatic search algorithm works is shown in Figure 2.

The secondary system visualization tool mainly realize the display of physical device hierarchical relationship, physical circuit display, "virtual and real correspondence" display of physical circuit and logic circuit. After the visualization tool import the SCD files and the SPCD files, at first, it enters the initialization, provides the analytical basis for the subsequent core automatic algorithm, and after the initialization, it enters the formal process of parsing, through three functional modules: the SPCD level parsing module, the SPCD display module and the SCD display module, analysis physical device
hierarchy, physical circuit, and logical circuit of IED device, and the "virtual reality correspondence" technology is adopted to complete the judgement of the information flow, to draw the panoramic information flow graph. The panoramic information flow graph can automatically switch between the virtual circuit and the real circuit. Through the real circuit connection, the virtual circuit line can be displayed, and the corresponding real circuit line can also be found through the virtual circuit line. The analysis flow of the SPCD file visualization tool is shown in the figure 3:

**Figure 2.** Core automatic search process
3.3. Smart substation secondary system evaluation technology

The secondary system evaluation technology, based on the full data of the secondary system operation of smart substation, establishes the secondary device on-line monitoring and state evaluation system which are based on the multi parameter information fusion. The state evaluation system includes two evaluation methods based on "trend" and "loss". The secondary device evaluation system of smart substation mainly includes evaluation objects, evaluation subitems and evaluation parameters. The relationship between each element is shown in Figure 4. In the evaluation system of figure 4, the evaluation object is the secondary physical device of the smart substation. Each evaluation object contains different evaluation subitems, and the state of each evaluation subitem is evaluated by multiple evaluation parameters. The state of the evaluation objects is calculated by the results of each subitem, and the operation state of the whole substation is obtained according to the state of all evaluation objects.

The health status of the relay protection device components can be divided into two cases, which are gradually changing with the running time and sudden variation. The former is known as trend assessment by monitoring data in a period of time, which is called trend assessment, and the latter determines the loss of function by reflecting the signal of the abnormal condition of the device, it is called a loss assessment.

Figure 3. Parsing method of SPCD file visualization tool
4. Trend assessment
The trend assessment method refers to the long-term monitoring and recording of the steady-state value of the device, reflecting the change trend of the component performance in a period of time, which include the accuracy of the sampling value, the consistency of the switch value, and the change of the other self inspection parameters of the device. This type of state is evaluated by the threshold value method, which is to alert the device component when the value of the monitored component exceeds a given threshold. Through the accumulation of long term operation data, the operation trend of smart device components is analyzed.

5. Loss assessment
The method of loss assessment means that when the device has abnormal alarm, the specific nature of the malfunction, such as the severity level, duration, range of influence and the most possible fault location, is inferred by analysis and statistics of the alarm information by type, that provides assistance for the defect handling.

Through the trend assessment and loss assessment, the smart substation secondary system can be comprehensively evaluated, and hidden hazards can be discovered in time, the alarm abnormality can be accurately judged, and the normal operation of the secondary equipment can be maintained.

5.1. Intelligent diagnosis technology for secondary system of smart substation
The intelligent diagnosis technology of the secondary system of smart substation is that when the fault or alarm occurs, which can be used to determine the fault source quickly and accurately.

The evaluation methods used in this technology include:
Secondary equipment fault diagnosis method based on fault characteristics, including sampling value anomaly evaluation of relay protection device, evaluation of synchronization anomaly between multiple MU and SV data of merging unit anomaly evaluation method.
The secondary circuit fault diagnosis method based on the proof table, is to use the normal communication link and the abnormal communication link as the corresponding physical channel node failure probability "proof", and then according to the results of multiparty proof to determine the most likely fault channel node, and implements the process layer channel fault positioning. The secondary system fault diagnosis method based on information association relationship refers to process the information that can characterize the working performance and condition of each part of the secondary system of the smart substation, and obtains the working condition and hardware state of each part of the relay protection, so as to determine the malfunction of secondary system. Through the above methods, the state of the two equipment id evaluated and the fault is diagnosed, that provides the final result of the health assessment of all the secondary devices.

6. Design of online monitoring and intelligent diagnosis system for intelligent secondary equipment

6.1. Function design

The smart substation secondary equipment online monitoring and intelligent diagnosis system mainly has three functional modules:
1) Secondary equipment status assessment and fault diagnosis module
The module includes smart substation secondary equipment state method and maintenance strategy based on multi-parameter identification, forms a typical fault diagnosis method and processing strategy for secondary equipment, and establishes a secondary sub-equipment state assessment and fault diagnosis system for smart substation, implements “Effective evaluation before abnormality, rapid positioning after abnormality.”
2) Secondary system network security detection module
Based on the IEC-61850 protocol of smart substation, the network information security detection rules are proposed. Through the information security detection system outside the physical isolation device, the abnormal or malicious behavior in the smart substation network is discovered, alerted and recorded in time to improve the network security of the smart substation.
3) Secondary equipment status monitoring and visualization module
This module implements the secondary system physical circuit modeling method, panoramic visualization display, the visual monitoring and analysis function of protection equipment and secondary circuit status, and lay the foundation for advanced application function modules, and provide functions for intelligent safety measures, fault diagnosis and network early warning. Visual display platform.

The specific display layout is shown in Figure 5.

![Figure 5. System platform architecture](image-url)
Divided into four layers. The first layer includes: one main wiring diagram and network topology diagram; the second layer includes: interval real wiring monitoring, interval virtual circuit monitoring, interval link monitoring, station control layer network monitoring; the third layer includes: protection status monitoring, protectionAlarm monitoring and protection action monitoring; the fourth layer includes: safety maintenance strategy generation, online calibration, and Anto offline simulation.

6.2. Overall architecture

The intelligent operation and maintenance system obtains information from the process layer network and the station control layer network, implements applications such as visual online monitoring and intelligent diagnosis, and supports the remote upload function. The smart substation visual operation and maintenance system is mainly composed of four levels of software shown in Figure 6.

![Figure 6. Software framework](image)

The research on common protection technology mainly includes the following aspects: The development of software and hardware platforms based on the requirements of high-precision synchronous characteristic detection technology; The network communication technology based on Ethernet; The network message synchronization technology based on EPGA hardware which can measure the synchronization delay of network packets accurately, implements the delay characteristic test of the network communication of the smart device; The network message editing and decoding technology based on the EPGA hardware which improves the network packet throughput capability and the transmission delay accuracy of the test platform.

The hardware framework is shown in the figure 7.
7. Practical example of smart substation secondary equipment fault and abnormality intelligent diagnosis system

7.1. Application environment

Taking the minimum system of 220kV smart substation as an example, a simulation platform is built in the laboratory based on the typical structure of 220kV direct sampling and direct outlet network of smart substation. The simulation platform has passed the dynamic model test and can simulate the operation and fault condition of the smart substation secondary system. The 220kV line structure is as shown in Figure 8:

![Figure 8. The minimum system of 220 kV smart substation](image)

The minimum system contains a total of seven intervals, one transformer interval, five line intervals, and one bus-link circuit breaker interval. 220kV voltage level relay protection device, merging unit and smart terminal, and process layer network are dual configuration.

7.2. Application

When a fault occurs at point k, for protections 1 and 2 are internal faults, under normal conditions, protection 1, 2, 5, and 6 are started at time t1, and protection 1 and 2 are operated at time t2, and protection 5 and 6 are returned. If the protections 1 and 2 are rejected, the protections 5 and 6 act as backup protection actions.

Taking the protection 6 startup abnormality as an example, the state evaluation and fault diagnosis system can use the multi-parameter identification evaluation technology. Comparing the the startup
status of the protection 5 and 6 based on the protection of the state information of 1, 2. Due to the protection 1, 2 and protection 5, 6 start the relationship is chain relationship, when the protection 1, 2 start, protection 5 start, but the protection 6 does not start, you can determine the protection 6 startup exception.

Taking the SV channel fault of protection 6 as an example, through the state assessment and the associated fault diagnosis function of the fault diagnosis system, the main secondary system fault type of the substation and the key conditions of the fault occurrence are combined with the secondary equipment operating state and the secondary circuit state, topology model, networking mode, circuit breaker displacement and circuit breaker status, telemetry, timing, etc. for correlation analysis and comprehensive diagnosis. In a certain time window, the analog protection device samples the interrupt alarm, and at the same time, detects and detects the protection device light. The port receives the power alarm, but at the same time, it detects that the measurement and control device is sampling normally, the communication message is monitored normally, and the network is normal. At this time, we can infer the SV channel failure of the protection device according to the multi-event correlation model. The reasoning and prompt diagrams are shown in the figure 9.

![Figure 9. Comprehensive diagnosis of protection SV channel fault](image)

Finally, taking the switching value collected by the first intelligent terminal of protection 2 is abnormal as an example. When a fault occurs at point k, the protection 2 is started (t2) under normal circumstances, and the circuit breaker is in the breaking position (t2+).

Since the protection 2 adopts a dual configuration, the state information between the two sets of intelligent terminals A and B has a redundant relationship. The state vectors of the intelligent terminal A and the intelligent terminal B are respectively \(X_{11x1}\) and \(X_{22x1}\). The elements in the state vector are the respective switch quantities collected by the intelligent terminal. \(H_{nx1}=X_{11x1}-X_{22x1}\). Then, the system searches \(H_{nx1}\). If finds there is a non-zero element, the position of the circuit breaker corresponding to the protection 2 is inconsistent, wherein the information of the first set is "1" and the second set is "0".

To further determine whether the abnormality is caused by the abnormal position of the circuit breaker itself or the information collected by the intelligent terminal is incorrect, the online monitoring method based on the physical law constraint relationship is used for judgment. Before the occurrence of short-circuit fault (t1-), the sampled value satisfies \(i_{L1}=i_{L2}+i_{L3}+i_{L4}, i_{L4}=i_{L5}+i_{L6}\). After fault removal (t2+), the sampled value satisfies \(i_{L1}=i_{L3}+i_{L4}, i_{L4}=i_{L5}+i_{L6}\). The above criteria can indirectly determine that protection 2 acts normally, the circuit breaker is in the breaking position, the status information is "0".

In summary, it can be determined that the switch quantity collected by the first set of intelligent terminal A of the protection 2 is abnormal.

7.3. Application effect

The simulation platform implements the establishment of the virtual reality correspondence...
relationship of the smart substation secondary system and the display of the secondary loop visualization that solves the problem that the secondary circuit of the smart substation is not visually visible. The platform establishes an evaluation system based on “trend” and “loss”, and obtains operational data of all devices including merging unit, intelligent terminal, protection measurement and control, switch, etc., evaluates the health status of the device, and solves the problem of real-time online assessment of secondary device operating status. The fault diagnosis function of the platform implements the secondary circuit fault positioning, which solves the problem that the operation and maintenance personnel are difficult to find the fault point on the site.

The smart substation secondary equipment defect and abnormality intelligent diagnosis system solves the problems of physical circuit expansion model, visual display, secondary equipment status evaluation, fault diagnosis and so on, and provides guarantee for efficient and reliable operation of smart substation.

8. Research summary

Aiming at the needs and issues faced by smart substation in the operation and maintenance of secondary equipment in recent years, this paper uses physical modeling to visualize the congruent relationship between virtual and reality. And, it establishes an evaluation system and fault diagnosis system based on “trend” and “loss”. The systems effectively solve the issue that the secondary circuit of the smart substation is not intuitive, they can implement real time monitoring of secondary circuit and are helpful to clear the fault to ensure the safety of smart substation.

9. References

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