Research on Fault Diagnosis and Location Technology of Secondary System Smart Substation

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Abstract. This paper for the secondary system fault diagnosis Smart Substation location problem. By using fault feature, evidence table and information relationships, the basic evaluation method of the sampling abnormalities of relay apparatus, synchronization abnormalities of multiple MUs, channels abnormalities and operation abnormalities is specifically analysed. An example based on information relationships is given and the functional structure of the secondary fault diagnosis and evaluation system of the main and substation modes is designed, which provides reference for the basic technical methods and implementation methods for the fault diagnosis and location of the secondary system of Smart Substation.

1. Introduction
At this stage, China's Smart Substation has developed rapidly in planning and construction, and its importance to the power grid is increasing. The operation of Smart Substation equipment and systems is closely related to the safety and stability of large power grids. Especially because the communication between secondary equipments in Smart Substations using the form of message interaction, the failure of one device may cause other devices connected to it to generate alarms due to communication interruption. The channel nodes corresponding to each communication link, such as devices, boards, ports, and optical fibers, are all possible fault points, so how to quickly identify the source of the fault, plays an important role in the rapid processing and recovery of the fault [1]. This paper conducted a comprehensive analysis of different principles, and verified by examples. At the same time, a functional structure of the secondary equipment state assessment system is designed for the realization of the Smart Substation secondary system fault diagnosis system.

2. Fault location diagnosis of secondary equipment based on fault characteristics
This section mainly uses the sampling anomaly characteristics of the secondary equipment of the Smart Substation to analyze the sampling value anomaly of the relay protection device, the synchronization anomaly between multiple MUs and the SV data anomaly of the merging unit, and gives a description of the evaluation method.
2.1. Sampling values abnormality of relay protection devices judgment method

The SV disconnection alarm issued by the relay protection device in the MMS report mode is monitored in real time [2], and the corresponding IED name in the SCD file, the RptID of the BRBCB, and the corresponding FCDA in the DataSet are parsed. Based on the protection apparatus’ MU (combining unit) which receives the sampling values in SCD file, APPID of the SVCB (SV control blocks) is configured. The station control layer MMS report is associated with the APPID of the process layer MU. If the data value corresponding to the FCDA in the protection device MMS reports is set or reset, further analysis is performed:

(1) Generally, it is determined that the merging unit is blocked when the network is not received by the SV;

(2) If the same MU associated directly collection protection (e.g., lines, poor female) are reported anomaly, it is determined that direct collection boards and cards of MU latch;

(3) Otherwise it is determined that the optical fiber loop is abnormal.

2.2. Multi MU synchronization abnormality judgment method

For the MU that uses the point-to-point connection mode, the cohort clock is connected for synchronization. When the first bit of the SV packet sent by the MU is received, the time stamp is set. And the deviation between the actual delay of the time corresponding to the packet with the labeling “0” and rated delay is less than 10µs; if SV messages take networking mode, check the sample count deviation between SVCB messages with different APPID which converted to time should not be more than 2ms; long-term monitoring the two sets of MU samples of the same CT, PT, Whether there are large deviations.

2.3. Combining unit SV data abnormality judgment method

After the SV packet sent by the MU is received, the SV packet is evaluated for various abnormalities, including: sample count deviation, transmission frequency jitter, and transmission delay deviation; ConfRev (configuration version), DataSet, SVID (SV identifier) The number of MAC entries does not match; timeout, packet loss, disordering, repetition, sampling sequence number error; quality change; double AD sampling inconsistency; traffic burst / burst; length parameter error, APDU (application protocol data unit), ASDU (The application service data unit is encoded incorrectly.

3. Secondary circuit fault diagnosis and positioning based on evidence table

Communication failures that occur during the operation of a secondary devices of a Smart Substation are usually caused by channel failures. When the device communication link monitoring function cannot locate the node, maintenance personnel need to check one by one according to the communication link status, which is also a common problem in the operation and maintenance of the Smart Substation. The secondary device physical port model is an important technical measure to realize the "virtual and real correspondence" between the communication virtual loop and the physical real loop, and is the basic model for secondary loop visualization and communication link fault diagnosis. The proposed Smart Substation process layer channel fault location method based on the evidence table is based on the secondary device physical port model specified in the Q/GDW 1396-2012 standard [3].

The physical port information and virtual loop information are extracted from the SCD file, and the physical channel node set corresponding to each virtual loop is obtained through topology search. The fault node set includes equipment, board, port and fiber [4]. The set of fault nodes of different virtual loops may cross, which is why a component fault of one channel in the process layer may cause multiple communication links to fail at the same time. Since multiple physical communication links are carried on one physical channel, physical channel failures can cause multiple communication links to fail at the same time. A channel failure is a sufficient condition for generating a communication failure. If the device communicates normally, its channel node must also be normal. When analyzing the communication link failure, it is necessary to check not only the channel node corresponding to the faulty communication link but also the possibility of the corresponding channel node being faulty.
according to the normal communication link, and narrowing the scope of the fault location. Therefore, the state of the communication link of the whole network devices is comprehensively utilized, and the normal communication link and the abnormal communication link are used as the evidence of the failure probability of the corresponding physical channel node, and then the channel nodes most likely to be faulty are judged according to the result of the multi-party certification. Realizing the fault location of the process layer channel, and the data model of the algorithm is called the fault evidence table.

4. Fault diagnosis and location of secondary system based on information association

The Smart Substation secondary system mainly includes components such as merging unit, intelligent terminal, process layer network and relay protection device [5]. The information that can characterize the performance and function realization of each part of the secondary system of the Smart Substation is called the status information of the relay protection of the Smart Substation in this paper. Taking Smart Substation relay protection equipment as an example, this section starts from the components of relay protection of Smart Substation, combs its state information, analyzes the correlation of state information, and studies a secondary system fault diagnosis and positioning method based on information association.

4.1. Smart Substation relay protection status information

Table 1 lists the status information of each part of the relay protection of the Smart Substation. The equipment status of the relay protection device mainly include the alarm of the relay protection device hardware and some secondary loop chain-broken alarms; The unit status of the unit and the status of the intelligent terminal equipment have the same focus is on the operation of the device hardware and the associated secondary loop; The state of the process layer network is primarily related to the switch state and network state. The above-mentioned types of status information mainly reflect the working conditions and hardware status of each part of the relay protection, and are relatively independent from each other. The state information that is mainly considered in this paper is the action component state of the relay protection device, the displacement state, the intermediate node state, the sampled values of the merging unit aggregation and transmission, and the switching amount collected and transmitted by the intelligent terminal.

Table 1. Smart substation relay protection status information

| Secondary system component | status information | Example |
|---------------------------|-------------------|---------|
| Relay protection device   | Ready state       | Protection device alarm |
|                           | Action component status | Actions of various types of protection |
|                           | Displacement state | Press plate retreat, fixed value modification |
|                           | Intermediate node status | Actions of intermediate nodes such as phase selection components and starting components |
| Merging unit               | equipment status  | Equipment running time, merging unit related secondary loop status |
|                           | sample value      | Sampling AC current and voltage value |
| Intelligent Terminal       | equipment status  | Equipment timing, intelligent terminal secondary loop status |
|                           | Switch            | Circuit breaker position |
| Process layer network     | Switch status     | PVID value |
|                           | network status    | Network delay, traffic |
4.2. Smart Substation relay protection status information association

Among the secondary system equipment of Smart Substation, the realization of relay protection function involves the most information content and equipment types, and the status information of relay protection status is also the most comprehensive. This section still uses Smart Substation relay protection as an example to illustrate relation between the secondary equipment statuses of Smart Substation. As shown in Fig. 1, table 2 gives specific meaning of 12 kinds of direct connections obtained according to the analysis of information.

![Relay Protection Device Diagram](image)

**Figure 1.** Relay protection status information association

**Table 2.** The specific meaning of the relationship of relay protection status information

| Serial number | Specific meaning                                                                 | Example                                                                 | Serial number | Specific meaning                                                                 | Example                                                                 |
|---------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------|---------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 1             | Coordination between various types of protection or redundant configuration of action elements | Main protection action, backup protection start but not action          | 7             | Relationship between displacement state and switching quantity                    | A protective pressure plate is withdrawn. If a fault occurs, the trip may not be exported, and the switch quantity will not change. |
| 2             | The relationship between the state of the action component and the state of the displacement | Functional platen retraction can affect the corresponding protection action | 8             | Association between two sets of protected intermediate node states in the same protection or redundancy configuration | A protection during operation, corresponding to the phase selection element member, the operation starting element should |
| 3             | The relationship between the state of the action component and                     | Protection action, the corresponding intermediate relay should act      | 9             | The relationship between the state of the intermediate                           | A sudden change in the sample value at the time of the fault will     |
|   | the state of the intermediate node | node and the sampled value | cause the starting element to act. |
|---|----------------------------------|---------------------------|-----------------------------------|
| 4 | The relationship between the state of the action component and the switch quantity | Busbar protection action, the switching quantity of the line connected to the busbar changes | Association between sampled values of two merged units in the same merged unit or redundant configuration | The current and voltage values between the bus and bus lines meet a certain numerical relationship |
| 5 | The relationship between the two sets of protected displacement states of the same protection or redundant configuration | Fixed value coordination between three sections of three-stage overcurrent protection | The relationship between sampled values and switching quantities | The amount of switching affects the primary side topology, which in turn affects the numerical relationship between sampled values. |
| 6 | The relationship between the displacement state and the state of the intermediate node | The fixed value changes, and the state of the corresponding protection intermediate node may change when the fault occurs. | The relationship between the switching quantity of two intelligent terminals of the same intelligent terminal or redundant configuration | If the busbar fails, the busbar circuit breakers on the busbar circuit breaker and the busbar should be disconnected. |

By combing these 12 kinds of relationships, we can find that these related relationships can be mainly divided into four categories: chain relationship, mutual exclusion relationship, redundancy relationship and physical law constraint relationship.

(1) The chain relationship is mainly for the state information of the Boolean type. This kind of information only has two values of “0” and “1”, which mainly includes the breaking state of various relays (the conduction is 1 and the disconnection is 0) and platen cast back situation conditions (pressure plate is put into 1, the platen exits to 0) and so on. The chain relation between two state information means that if one of the information A, the another information is also A. The status information with a chain relationship in the relay protection system usually exists between the links that are inevitably started by the same relay protection action or within the same type of link the relay protection device. For example, when a line ground short circuit fault occurs, under normal circumstances, the current change amount starting element and the zero sequence overcurrent starting element inside the relay protection device are all operated, and the state of the corresponding phase selecting element and the protection logic relay also changes. The main relationships in Table 2 are the associations 1~9 and 12.

(2) The mutual exclusion relationship is also mainly directed to the state information of the Boolean type. The mutual exclusion relationship between two state information means that if one of the information is A, the other state must not be A. In other words, for two state information with mutually exclusive relationship, if one of them is 1, the other must be 0, and vice versa. The status information with mutual exclusion relationship in the relay protection system generally refers to the position of the circuit breaker and the action of the relay of the trip position. Under normal circumstances, the circuit breaker can only be in the closed or open state, there is no intermediate state; when the trip position...
relay is in the closed position, the closing position relay must be in the open position. The states in Table 2 that satisfy the mutual exclusion relationship are mainly the associations 1–8 and 12.

(3) A redundant relationship between two state information means that the two state information are always consistent. Redundancy can be applied to the Boolean type and other types of status information, wherein the value of non-Boolean type status information is not only "0" and "1", which includes sample values, device temperature, network delay. Status information with redundant relationships typically exists in the protection of a dual configuration or in two sampled values and switching quantities with a source of homologous information. The states in Table 2 that satisfy the redundancy relationship are mainly the associations 1, 5, 8, 10, and 12. There is no electrical or network connection between the protection of the dual configuration of the intelligent station. Therefore, the reception and processing of the dual protection information of the Smart Substation are independent, and the same state information has a certain redundancy relationship, that is, two states remain. Consistent. For single-density configuration protection, if the primary protection and backup protection are respectively configured by two sets of relay protection devices, the AC secondary circuits are usually independent of each other, but are taken from the same primary system sampling value; for primary protection and backup the protection configuration is protected by a single configuration of a protection device. The AC sample value of the device and the AC sample value of other devices (such as the measurement and control device) in the same interval are taken from the same information source. Therefore, to a certain extent, the protection of the single-weight configuration also has certain information redundancy characteristics.

(4) The physical law constraint relationship is mainly for the sampled value. Associations 10 and 11 that satisfy the constraints of the physical laws. Whether it is the relationship between sampled values or the relationship between the switch quantity and the sampled value, it can be understood as the constraint relationship between the sampled values when Kirchhoff's law is satisfied. In other words, the sampling value under a certain system topology should satisfy a certain physical law constraint relationship.

4.3. Secondary system fault diagnosis method based on state information association relationship

According to the characteristics of the chain relationship, if two state information with a chain relationship has a large deviation, it can be judged that an abnormality occurs in a certain state information. Specifically, the secondary system fault diagnosis can be realized by constructing the exclusive OR logic: if the two state informations having the interlocking relationship are different, the output is 1, that is, the output state abnormal signal.

According to the characteristics of the mutually exclusive relationship, if two state information with mutually exclusive relationship do not appear complementary, it can be determined that an abnormality occurs in a certain state information. Specifically, the secondary system fault diagnosis can be realized by constructing XNOR logic: if both state information with mutual exclusion relationship are both 1 or 0, the XNOR logical output is 1, that is, the output state abnormal signal.

The secondary system state relationship is divided into two types: Boolean type redundancy state information and non-Boolean redundancy state information, and fault diagnosis methods based on these two types of state information are respectively established. Suppose a protection components have a total of n number of Boolean type of status information \( x_1(t), x_2(t), \ldots, x_n(t) \), are regarded as components of a vector \( X_{n \times 1}(t) \), so the \( X_{n \times 1}(t) \) is the n-dimensional state vector of composition portions of the protection, shown in the following formula:

\[
X_{n \times 1}(t) = [x_1(t) \quad x_2(t) \quad \cdots \quad x_n(t)]^T
\]

Assuming that the two state vectors with redundant relationship are \( X_{1n \times 1} \) and \( X_{2n \times 1} \) respectively, then in the same power system state, the elements in \( X_{1n \times 1} \) and \( X_{2n \times 1} \) should theoretically be identical. Therefore, by comparing these two state vectors, it is possible to find some abnormalities in the relay protection. In the case where only the Boolean type state information is compared, the two state vectors are subtracted, and the resulting matrix \( H_{n \times 1} \) is searched for a non-zero element. Under normal
circumstances, the number of non-zero elements should be 0 if it is not 0, you can locate which state information is abnormal by searching for non-zero elements in HN×1. For example, if the i-th row element of the matrix HN×1 is not 0, the i-th state information corresponding to X1n×1 or X2n×1 is abnormal. As described above, in protection systems, non-Boolean status information mainly refers to sample values and the like. In order to determine its accuracy, it may be by comparing the differences between the information to find that certain Relay System abnormal.

There are a large number of system status information from primary system in the secondary system, including three-phase voltage, phase current, active power, zero-sequence current, etc., redundant relationship based on the physical constraints present among these information. By collecting and determining such information in the secondary system, it is possible to diagnose the secondary system logic loop and device status. In order to better realize the fault diagnosis of the sampled values, the constraint relationship between the relay protection state information can be fully utilized: different circuit breaker position combinations or wiring modes correspond to different primary system topologies, and corresponding sampling values will be different, sampling the physical law constraint relationships that are satisfied between values also change.

4.4. Example analysis
To verify the validity of the secondary system failure diagnosis method, the present text will take minimum system of a 220kV Smart Substation as an example to analysis. As shown in FIG 2, this minimum system contains 7 intervals 1 transformers interval, 5 circuit intervals, and 1 bus tie breaker interval. The relay protection device, the merging unit and the intelligent terminal of the 220kV voltage grade, and the process layer network are all configured in a dual configuration.

![Figure 2. Smart Substation Min - System Analysis Case](image)

The enumeration of status information is shown in Table 3 below:

| Association relationship | State Information 1                             | State Information 2                             |
|--------------------------|----------------------------------------------|----------------------------------------------|
| Chain                    | Protection 5,6 startup \((t_1)\)               | Protection 1,2 startup\((t_1)\)               |
|                          | Phase selection component and startup component of Protection 1,2 operate \((t_1- t_2)\) | Protection 1,2 operate \((t_2)\)               |
|                          | Circuit breakers corresponding to protection 1,2 are in opened position \((t_2+)\) | Protection 1,2 operate \((t_2+)\)               |
|                          | Protection 5,6 operate \((t_2+)\)            | Protection 1,2 operate \((t_2+)\)            |
Take the protection 6 start abnormality as an example. Based on the state information of protection 1 and 2, the reference state vector at time $t_1$ is $y(t_1)$, and each element in the vector represents the start condition of protection 1 and protection 2, respectively, 1 for starting and 0 for not starting; The comparison state vector at time $t_1$ is $x(t_1)$, and each element in the vector represents the start condition of protection 5 and 6, respectively, then these is:

$$x(t_1) \oplus y(t_1) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \oplus \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

The second row of the matrix obtained by the operation is not 0, so it is possible to judge the startup abnormality of the protection 6. To further determine that the abnormality is due to the startup component abnormality of protection 6, or the fallacious sample values of protective 6 combining unit, fault diagnosis method based on physical laws constraints can be used. Before the short-circuit fault occurs ($t_1-$), the primary topology state vector is $Z_{10 \times 1}(t_1-)=\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$, and accordingly, the sample value satisfies $i_{L1} = i_{L2} + i_{L3} + i_{L4}$, $i_{L4} = i_{L5} + i_{L6}$; Similarly, it is found that $Z \in \times 1$ ($t_2+$) and the sample value meet the physical law constraint relationship after the fault removed, thereby judging that the sample value is normal. In summary, the protection 6 startup component abnormality can be initially determined.

5. Functional architecture design of secondary fault diagnosis and evaluation system

Based on the above analysis methods, the functional architecture of the secondary fault diagnosis and evaluation system designed in this paper is shown in Figure 3. The main-substation mode is mainly used.

In the assessment system, system parameters configuration, communication settings, basic maintenance, secondary equipment health status real-time analysis, fault diagnosis of secondary status display and a secondary device fault diagnostic status display and other major features are implemented in main station. Typical hardware configurations include comprehensive diagnostic assessments Server, maintenance engineer station, graphical display monitor, and web server.

The assessment system sub-station realizes the main functions such as message collection and display, evaluation index extraction, sub-item evaluation and comprehensive evaluation results. The sub-station is arranged in the substation, and the corresponding function can be added on the basis of the newly added independent device or based on the original network message analyzer. The implementation of
the evaluation method includes the mutual verification of the logic between the messages and the real-time detection of the health status of the messages by the evaluation system.

![Diagram of Secondary fault diagnosis and evaluation system functional architecture](image)

**Figure 3.** Secondary fault diagnosis and evaluation system functional architecture

In the algorithm for evaluating the secondary device, the final score of the device is obtained by weighting the calculation items of each device, and the evaluation period of the device can be adjusted as needed. The period of the trend evaluation algorithm is 10 minutes, and the loss assessment is performed in real time. For other evaluation parameters, such as running time, family defects, etc., there is a separate interface for management personnel to enter, and participate in the evaluation of the device as a whole. During an evaluation period, the deduction of the device is cumulative and irreversible, that is, the abnormality occurring in this cycle, if it is eliminated, the normal value is restored in the next cycle, and is not restored in this cycle; if not, the next is Continue to maintain a low score during the cycle. The running time parameter of the device is irreversible, that is, as the running time of the device increases, the score of the device shows a downward trend according to the time period. After 12 years, the proportion of the device gradually increases, that is, the falling speed of the device is accelerated.
6. Summary
The operation of Smart Substation equipment and system is closely related to the safety and stability of the large power grid. It is especially necessary for the research and application of fault diagnosis and location technology for the secondary system of Smart Substation. Based on the analysis methods such as fault characteristics, evidence table and information relationship, this paper makes a basic evaluation and analysis on the abnormal value of the relay protection device, the synchronization anomaly between multiple MUs, the channel anomaly and the behavioral behavior anomaly. The example of the minimum system of Smart Substation is given to verify the analysis method based on information association relationship, and a functional architecture of the secondary fault diagnosis and evaluation system using the master - substation mode is designed to realize the application of comprehensive diagnostic evaluation technology. Provide a practical reference. In the next step, using artificial intelligence algorithm to optimize and improve the quality of fault diagnosis and location of Smart Substation secondary system will become the key application direction of the research.

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