Research on Real-time Reliability of Relay Protection System in Intelligent Substation

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Abstract. Because the intelligent substation is composed of a variety of intelligent electronic components, various types of information data will be generated during its operation. With the continuous implementation and rapid development of smart grid construction, the application of smart substations in power systems is becoming more and more extensive, and the number and scope of use are gradually expanding. In the face of the substantial increase in the commissioning of smart substations, people are paying more attention to the reliability of relay protection devices in smart substations during use. Strengthening research on the relay protection system of intelligent substations and improving the reliability of the system are urgent problems that need to be solved. The digitization of data information of the whole station is a typical feature of intelligent substations, on this basis, distributed relay protection can be realized; At the same time, the system-level status information can be identified and evaluated. Because there are too many spatial states, the calculation is very complicated. To solve this problem, this paper proposes to calculate the reliability of the relay protection device by Markov method, and then calculate in system level by GO method. Combining the Markov algorithm model with the GO method, the reliability of the relay protection system is calculated and analyzed, enabling the on-site operation and maintenance personnel to grasp the basic status of the relay protection device and the system operation in real time, obtain real-time feedback information, and better relay protection work of smart substations.

1. Introduction
Under the current circumstances, for the protection and regulation of intelligent substations, integrated and coordinated operations have basically been achieved, and the conditions for interconnection between different systems have been established; At the same time, the interaction level of relay protection in smart substations has been greatly improved, which can achieve good protection and control of substations, and escort the quality, quantity, safety, and stable operation of the power grid. However, since the level of intelligence in my country's substations is still at a relatively low level, it is still being continuously improved. In this case, there are still some problems in relay protection. On the one hand, the substation is gradually developing in the direction of intelligence, but the quality of the personnel engaged in substation-related work has not been improved accordingly. There is a phenomenon that the basic quality of the substation staff does not match the actual job requirements and does not meet the needs of the development of the times; On the other hand, due to the lack of complete protection measures in the substation, the relay protection system has potential safety hazards that are prone to failure, and safety accidents occur in some places. In view of the current development status of smart substations, the safety and reliability of their relay protection systems need to improve.
2. Features and structure of smart substation

2.1. Features of smart substation
With the promulgation of the IEC 61850 standard, the bay and process layers have taken over the functions of the original protection devices in the smart substation, forming a three-layer two-network structure; In the intelligent implementation of the primary equipment, the primary information collection part adopts the method of adding a merger unit with a circuit breaker combined with an intelligent terminal and an electronic transformer; In the realization of the networking of secondary equipment, conventional cables are replaced by optical fibers, and information transmission is carried out by intelligent equipment such as intelligent terminals, merging units, and switches. Its characteristics mainly include the following aspects.

Structured network. The system of the intelligent substation is set up in the manner of three layers and two networks, and then the system structure is constructed according to the IEC 61850 protocol.

Monitoring modularity. According to standards such as "Technical Guidelines for Intelligent Substations", intelligent substations implement various monitoring functions; Among them, based on the unified standard communication protocol, various detection items can be flexibly configured to avoid unnecessary conflicts.

Detection digitization. When intelligently detecting system equipment, digitally process data such as switch opening and closing status and equipment temperature; The digitized state parameters can be more easily measured and transmitted, and the detected results are transmitted to the process layer and station control layer.

Panoramic monitoring. The intelligent substation can realize the comprehensive real-time monitoring of the status of various equipment, including important equipment such as relay protection devices and primary equipment, so as to achieve panoramic detection of targets. This is a major advantage of intelligent substations.

Information integration. In the intelligent substation, various data information can be highly shared, and the station control layer uses an integrated platform to connect with the power data network. The integrated data information is processed on the integrated platform in the station to complete the integration of integrated monitoring and diagnostic information, thereby improving the work efficiency of the system in the station and the utilization of data information.

2.2. Structure of smart substation
In the IEC61850 protocol, the three-layer structure of the intelligent substation is clearly defined, and the functions of the relay protection system of the intelligent substation are defined hierarchically.

Figure 1 shows the structure of the relay protection system of the intelligent substation.

![Figure 1. Structure of relay protection system of intelligent substation](image-url)
3. Reliability model and status division of relay protection system

3.1. System reliability model
After obtaining the protection device message information, we divide the state of the protection device, and use the Markov model to calculate the real-time state probability distribution of the single relay protection device; Then draw the GO diagram of the protection system according to the structure diagram of the protection system and combine it with the reliability data of the protection equipment. Using the GO calculation method, the state probability distribution of the relay protection system is obtained.

![Diagram of GO calculation method](image)

3.2. State division
After the online monitoring function is realized, we can obtain the change information in time for the change status of the substation relay protection device. However, in the substation, since there are many relay protection devices, and each protection device has a variety of information, it is necessary to analyze a very large amount of data during analyzing. Analyze and summarize a large number of example messages. When using the Markov method to calculate reliability, the smaller the state space is, the faster the calculation speed is. In order to ensure the real-time nature of the calculation method, according to the message data is divided into different categories, the above status is classified into three categories, as shown in Table 1, to facilitate the next step of analysis.

| State classification                   | Fault category                                                                 |
|---------------------------------------|-------------------------------------------------------------------------------|
| Poor quality of protection equipment  | Abnormal current measurement collection, abnormal voltage measurement collection, unconfirmed operation |
| Abnormal protection equipment         | Abnormal data, abnormal switch collection, abnormal start, abnormal output    |
| Protection equipment failure          | Functional hardware failure, communication failure, software failure, power failure, configuration error, communication failure, clock synchronization failure |

According to the summary classification of the message data, the protection equipment can be divided into the following five states.
(1) The poor quality of the protection equipment has been found to be in a state of 1 by self-test. This state indicates that the message information of the relay protection device has abnormal quality bits. Possible causes include abnormal voltage measurement collection, abnormal current measurement collection, and unconfirmed operation.

(2) Abnormal protection equipment was found to be in state 2 by self-test. This state indicates that abnormal alarm information was detected in the IED device or network switching device in the intelligent substation. Possible causes include abnormal startup, data abnormality, abnormal output amount, and abnormal digital acquisition.

(3) The protection device failure was found in state 3 by self-test. This state indicates that the IED device or network switching device in the intelligent station detected a failure alarm message. Possible causes include functional hardware failure, software failure, configuration error, communication failure, power failure, clock synchronization malfunction.

(4) Overhaul found abnormal state 4. This state indicates that the patrol personnel found that the relay protection device was abnormal. The failure information was not shown in the message.

(5) The normal state is 0. In this state, the relay protection is in the normal working state.

The state relationship diagram is shown in Figure 2. Treat the various kinds of alarm information found as the original feature quantities and use the same method as the self-checking of various original feature quantities, that is, the sum of the number of various reasons that occurred during the operation evaluation / evaluation time area value $T_0$. The repair rate refers to the sum of the number of times each state is restored to the normal state / value of the evaluation time area $T_0$, $T_0$ refers to the cumulative running time of the bit.

![State relationship diagram of relay protection device](image)

Figure 3. State relationship diagram of relay protection device

4. Reliability analysis

4.1. Reliability index

Reliability represents the probability that the system will successfully perform the corresponding function under the specified environment, time, and conditions. System reliability is the key indicator to measure whether a system can operate safely and stably. Usually, when we analyze the reliability of the relay protection system, we use two methods: smart components and the overall system. To analyze the reliability of the relay protection system, it is necessary to evaluate the reliability of the entire system, and at the same time, the importance of the components themselves must be fully considered.

During reliability analysis, if the system fails, it can be restored to its original working state after maintenance, which is called a repairable system; On the contrary, if the system fails to resume operation after repair, or requires excessive maintenance costs to recover, it is called an unrepairable system. The intelligent substation relay protection system studied in this paper is a repairable system.

When evaluating the reliability of a relay protection system for an intelligent substation, this paper adopts three reliability indicators: reliability, mean time to failure (MTTF), and availability, and
introduces “probability of rejection” and “probability of misoperation” to protect the Analysis of reliability and security.

4.2. Case study

Based on the data of a certain intelligent substation for a period of time, the reliability of the 220kV line protection system of the intelligent substation is analyzed. First of all, according to the SCD file, the equipment related to the line protection is analyzed, and the corresponding intelligent terminal, merging unit and protection device are found. Then classify and integrate the message information of these four devices and record the number of occurrences of each state. Among them, state 4 (anomaly found during inspection) is the data collected on the spot.

Taking the merging unit as an example, first input the message sent by the merging unit into the message analysis software, sort and sort the message information, and obtain the transition probability between the states defined in this article.

Table 2. Merge unit status records

| P₀₁ | P₀₂ | P₀₃ | P₀₄ | P₁₀ | P₂₀ | P₃₀ |
|-----|-----|-----|-----|-----|-----|-----|
| 0.375 | 0.235 | 0.002 | 0.002 | 0.358 | 0.197 | 0.003 |

And use Markov model to generate state transition matrix.

\[
P = \begin{bmatrix}
0.386 & 0.375 & 0.235 & 0.002 & 0.002 \\
0.358 & 0.642 & 0 & 0 & 0 \\
0.197 & 0 & 0.803 & 0 & 0 \\
0.003 & 0 & 0 & 9.997 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1)

Statistics the state time of the merged unit. The state time of the merged unit is shown in Table 3. e₀, e₁, e₂, e₃, e₄ corresponding to the state time of the five states within the statistical time, in seconds. In the actual running process, this state time will change in real time with the running time.

Table 3. Merging unit status time

| e₀   | e₁   | e₂   | e₃   | e₄   | total |
|------|------|------|------|------|-------|
| 1152963 | 19210 | 9828 | 301  | 251  | 1182553 |

The resident matrix can be obtained from the data in the table.

\[
A = [q₀, q₁, q₂, q₃, q₄]^T
\]

(2)

\[
P = \begin{bmatrix}
0.97497 \\
0.01623 \\
0.00832 \\
0.00025 \\
0.00022
\end{bmatrix}
\]

(3)

The probability of occurrence of each state is calculated as q₀=0.9662, q₁=0.0249, q₂=0.0084, q₃=0.0003, q₄=0.0002.

In the same way, the state probabilities of other equipments are calculated. See Table 4 for the state probabilities of the equipments protected by this line.

Table 4. State probabilities of line protection equipment

| State probability | Merge unit 1 | Merge unit 2 | Protection device 1 | Protection device 2 | Smart Terminal 1 | Smart Terminal 2 |
|-------------------|-------------|-------------|--------------------|--------------------|------------------|------------------|
| q₀                | 0.9663      | 0.9541      | 0.9636             | 0.9592             | 0.9537           | 0.9688           |
| q₁                | 0.0248      | 0.0303      | 0.0247             | 0.0258             | 0.0325           | 0.0295           |
In the operation symbol, the former number represents the type number of the operator, and the latter number represents the operator number. Take the state probabilities of each device in Table 4 as input values, correspondingly input six operators of 1,2,3,4,8,9 as type 5 input signals. After MATLAB operation, the probability of signal 12 is obtained, which is the state probability of the line protection system \( q_0 = 0.9663, q_1 = 0.0248, q_2 = 0.0083, q_3 = 0.0002, q_4 = 0.0002 \). According to the multi-state characteristics of the relay protection device, the GO method is used to solve the real-time reliability of the relay protection system, so as to obtain the real-time state distribution probability of the system.

5. Conclusion
The status of smart substations in the power system is becoming more and more important, and its applications have been fully deployed and gradually developed. This article introduces the structure and characteristics of smart substations, and discusses in detail the components that affect reliability in relay protection of smart substations. During the operation of the intelligent substation relay protection system, many factors will affect its operation, such as the equipment, power grid structure, network conditions and protection device configuration in the station. It is proposed to use Markov model to calculate and analyze the device, and then use the GO method to analyze the real-time reliability of the relay protection system. This method can effectively reduce the state space of the Markov model, simplify the calculation method, and thus realize the function of rapid reliability real-time analysis of the intelligent transformer relay protection system.

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