Research on Online Verification of Relay Protection Setting Value Based on Multi-source Information Fusion Technology and Bow-tie Model

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Abstract. In view of the complexity and flexibility of the current power grid, in order to make relay protection online verification more accurate and effective, a protection importance degree sequence assessment method based on the multi-source information fusion technology and bow-tie model is proposed. Firstly, the cause of incorrect protection actions is analyzed by establishing a fault tree through multi-source information fusion technology, and the event tree analysis method is used to deduce the final development result of the event. Combined with the fault tree and the event tree, a bow-tie model is formed to visually and completely describe the whole process of the event. Then the economic loss of the event is analyzed as the basis for assessing the protection importance degree, and the online inspection of the protection setting value is completed from high to low according to the importance degree sequence. Finally, the IEEE 3-machine 9-bus system is used to verify the correctness and rationality of the method through simulation.

1. Introduction
As one of the most important secondary equipment in the power system, the incorrect action of the relay protection device will lead to a large increase in the probability of power grid outages and cascading failures.¹⁻³ In order to ensure the safe and reliable operation of the power grid and reduce the incidence of accidents, online verification of relay protection is very necessary and important. The traditional online verification method has the disadvantages of blindness verification, not suitable for the complex and huge power system network nowadays. Therefore, an online verification method based on the importance of protection ranking can be used to ensure that devices with higher importance (such as core hub stations) are prioritized for verification, thereby improving the calculation efficiency of verification.

Many scholars have studied on the improvement plan of online verification technology. Reference [4]systematically introduces the online verification and early warning technology of relay protection settings, and focuses on the verification methods of relay protection selectivity. Reference[5]considers the directionality of branch power during the verification process, and introduces the concept of information entropy to optimize the verification method. Reference[6]improves the verification method by analyzing the importance of branch protection devices and comprehensively considering the severity of power grid accident consequences. Reference[7]evaluates the consequences of protection failures by defining the importance of static and dynamic protection and combining event tree analysis.
When the above authors evaluate the importance of protection, most of the methods are based on the assessment and analysis of the severity of the consequences of the accident, but they ignore the causes of the accident. Therefore, the above method cannot systematically and comprehensively restore the antecedents and consequences of the entire event, and cannot provide an intuitive and clear visual assessment of the hazardous event. This paper uses multi-source information fusion technology and bow tie model to build fault tree and event tree, and puts forward strong preventive measures by analyzing the root causes and consequences of improper protection to reduce the occurrence of accidents. After the model analysis is completed, the economy of the loss load of the hazardous event is calculated as an indicator for evaluating the importance of protection, so as to determine the protection setting verification sequence.

2. Multi-source Information Fusion Technology

In order to analyze the technical problem with the multi-dimensional characteristics of the incorrect operation of the protection device, the available data include real-time data of state information, historical data of state information, and power grid operation data. Firstly, data mining is performed on real-time data of state information. Due to the diversity of information in the era of big data, in order to better combine the correlation between massive data, cluster recognition can be used to decompose big data into small sample data. Among them, structured data can be used for the state detection of power grid resources, and unstructured data obtained after deep learning feature extraction can be used for events such as troubleshooting. Then, through analyzing the historical data of the state information, the data samples of various lines in the previous years are obtained, and the real-time data of the state information is combined with the grid operation data to perform multi-source information fusion processing. Multi-source information fusion refers to the three-level information fusion of initial data, feature information extracted by processing and decision information obtained after evaluation, including primary fusion of data and features and high-level decision-level fusion. Finally, combined with the load-bearing capacity of the line, changes in electrical load and the status of the transformer equipment to analyze the causes of the misoperation of the protection device.

3. Bow-tie Analysis

3.1. Bow-tie model

The Bow-tie model is composed of two parts: the fault tree and the event tree. The model can completely restore the entire process from the occurrence of the target event to the result, thereby providing proactive risk prevention and control measures for the event. As shown in Figure 1, the top event is used as the split point, and the left half of the model is the fault tree. The fault tree uses the top event as the initial point to deducively infer the cause of the event, and then form a logical tree according to the logical relationship among them. Use fault tree combined with Bollinger logic combination analysis to analyze fault events qualitatively or quantitatively. The right half is the event tree. The theoretical basis of the tree is: from the beginning to the end, the event has various consequences of varying severity, because there are always two possibilities of success or failure in the middle link. The dynamic development of the event will be fan-shaped branches, which will be interpreted as different accident results.

Bow-tie model generally consists of the following elements: 1) Source of risk: the root cause of the accident, also known as the bottom event; 2) Fault tree: deducing the source of events (dangerous sources) by analyzing changes in events; 3) Top event: the target event, from which the fault tree and event tree are derived; 4) Event tree: take the initial event as the starting point and evolve step by step into the final event; 5) Result event: the risk result obtained after the evolution of the accident tree.
3.2. Protection fault bow-tie model

Taking the protection device incorrect action event as the top event, analyze its fault tree structure. Analysis of technology combining multi-source information fusion, the reasons for protecting the incorrect action are as follows: 1) Misoperation of this line due to refusal of other lines; 2) The operation mode is changed and the protection cannot be adjusted in time; 3) Protection setting error; 4) Protection configuration error; 5) Sampling value error; 6) Breaker failure.

The failure event is used as the initial event to analyze the event tree structure. By judging whether the power flow on the line exceeds its own load capacity, the event tree is finally divided into two types of accident consequences: line is not overloaded and line overload causes load loss. So far, the cause and consequence of the event have been analyzed, and the bow-tie diagram is drawn as shown in Figure 2.

In Figure 2, $X_1 = \text{Malfunction of this line due to refusal of other lines}$; $X_2 = \text{The protection mode cannot be adjusted in time due to the change of operating mode}$; $X_3 = \text{Protection setting error}$; $X_4 =$...
Protection configuration error; $X_5 =$ Sampling value error; $X_6 =$ Circuit breaker failure; $X_7 =$ Line running status

4. Risk Theory

4.1. Overview of risk theory
Risk value is defined as the product of probability and consequence, and can be used to assess the severity of the accident consequence when the relay protection is not acting correctly. The specific expression is as follows:

$$R = PI$$

(1)

In the formula, $R$ is the accident risk value caused by incorrect protection action; $P$ is the probability of occurrence of incorrect protection action; $I$ is the severity of the consequences caused by incorrect protection action, here only consider the value of load loss due to line overload.

Then the risk value due to incorrect action of protection $k$ can be expressed as:

$$R(k) = R_w + R_j = P_w I_w + P_j I_j$$

(2)

Where $R_w$ is the accident risk value caused by protection misoperation, $R_j$ is the accident risk value caused by protection refusal to operate; $P_w$ is the probability of protection misoperation; $I_w$ is the load loss value caused by protection misoperation; $P_j$ is the probability of protection refusal to occur; $I_j$ is the value of load shedding loss caused by protection refusal.

When determining the sequence of verification values, the methods and angles chosen by each literature to calculate the risk value are different, so it is difficult to verify its correctness. Therefore, this article uses a more intuitive method to define the protection importance, and calculates the economic loss caused by the incorrect action of the protection as an indicator to measure the protection importance.

The economic loss of power outage caused by load shedding is generally composed of two parts: power industry power outage loss and power user's power outage loss. This section will mainly explain in detail from these two parts.

4.2. Economic losses in the power industry
The main task of the power industry is to provide power users with safe, reliable, stable, and high-quality electrical energy at reasonable electricity prices. In the event of a line overload accident due to the inability of relay protection to operate correctly, in order to ensure reliable power supply to the power system and prevent large-scale blackouts, part of the load must be cut off. The load shedding will cause huge economic losses to the power grid and major power groups. The losses include the reduction in sales revenue due to the decline in the volatility of electricity sales, the cost of cutting off the power load and the economics of equipment maintenance loss fees. Among them, the loss of electricity sales accounts for the largest proportion of the total loss, and it is the main evaluation index of the economic loss of load-shedding of the power system.

The load loss economic loss function of the power industry is:

$$M_1 = ULT$$

(3)

Where $M_1$ is the economic loss of the power industry; $U$ is the price of electricity sold in the power industry; $L$ is the load shedding; $T$ is the length of power outages for power users.

4.3. Economic losses of power users
The power user is the terminal of the power transmission chain of the power system and belongs to the direct consumer of the power. Therefore, cutting off the power load due to an accident will inevitably cause a certain amount of economic loss to the user directly or indirectly. However, due to the different power consumption characteristics and time periods of power users in different industries, the economic
benefits lost during power outages are naturally different. In order to simplify the calculation process and improve the verification efficiency, only the losses of industrial users are considered here. Industrial users account for a large proportion of the total electricity consumption in the society, and the impact of power outages is more serious than other industries, which is specifically manifested in two points: 1) Production machines are shut down due to power outages during the production process, resulting in products Loss of profits due to production suspension and damage; 2) The cost of restarting the machine during the recovery from the shutdown to normal operation.

In order to reasonably estimate the economic losses of industrial users during power outages, this paper collects data on industrial production areas of a city through questionnaires. According to survey statistics, the economic profit loss values of typical industrial users in the city under different power outage durations are shown in the following table:

| Power outage duration(h) | 0.5  | 1    | 2    | 4    | 6    |
|--------------------------|------|------|------|------|------|
| Industry loss(yuan/kW)   | 5.34 | 10.53| 20.98| 41.74| 79.81|
| Power outage duration(h) | 8    | 10   | 15   | 24   | -    |
| Industry loss(yuan/ kW)  | 127.72| 183.47| 326.56| 544.18| -    |

Then the least square method data fitting is used to obtain the economic loss function $K$ per unit time outage:

$$K = -0.48t^3 + 1.99t^2 + 2.44t + 5.34 \quad (4)$$

The load economic loss function of power users is:

$$M_2 = KL \quad (5)$$

In the formula, $t$ is the duration of power outage; $M_2$ is the economic profit loss value of power industry users; $L$ is the amount of load shedding.

Through the above analysis, the total economic loss value is the sum of the economic loss of the power industry and the economic loss of the power users:

$$M = M_1 + M_2 \quad (6)$$

5. Case Analysis

According to the above method, the regional grid relay protection setting value verification software system based on the Oracle database as the access platform is developed. The system is a three-level system structure with two calculation data interfaces, which can effectively complete the calculation of power flow distribution and the verification of relay protection settings. This article takes the IEEE 3-machine 9-bus system standard system as an example, uses the power flow calculation module in the system to calculate its load loss, and ranks the importance of protection using the above method. Finally, the online verification module is used to complete the verification of the relay protection settings.
The load loss caused by the misoperation and refusal of each line protection is calculated by the power flow calculation module, and then the corresponding economic losses are calculated by equations (3) and (5), thereby determining the order of protection setting value verification:

| Protection | Misoperation loss | Refusal to lose | Comprehensive Risk Index | Economic losses | Verification sequence |
|------------|------------------|----------------|--------------------------|-----------------|-----------------------|
| 1          | 0                | 25             | 1.6380375                | 340.5864        | 11                    |
| 2          | 0                | 90             | 6.2073                   | 1226.11104      | 5                     |
| 3          | 0                | 90             | 6.145227                 | 1226.11104      | 6                     |
| 4          | 0                | 25             | 1.6568475                | 340.5864        | 10                    |
| 5          | 0                | 25             | 1.7258175                | 340.5864        | 9                     |
| 6          | 0                | 100            | 6.82176                  | 1362.3456       | 4                     |
| 7          | 0                | 100            | 6.82803                  | 1362.3456       | 3                     |
| 8          | 0                | 25             | 1.6098225                | 340.5864        | 12                    |
| 9          | 25               | 25             | 3.401055                 | 673.0248        | 7                     |
| 10         | 25               | 125            | 9.7328325                | 2035.3704       | 1                     |
| 11         | 25               | 125            | 9.70473                  | 2035.3704       | 2                     |
| 12         | 25               | 25             | 3.2244975                | 673.0248        | 8                     |

From the above table, protection 10, 11, 6, 7 is more important, so the corresponding line will be checked first. This is because the active power of the No. 3 generator is larger, which causes more load to be cut off on the branches connected to the output, and the economic loss is also increased. While prioritizing these several lines, protection measures and preventive measures should be strengthened for these key lines. According to the analysis of the fault tree in the bow-tie model proposed above, the protection team can strengthen the manual inspection from the aspects of checking the soft pressure plate, proofing the protection settings and configuration, etc. The protection and setting personnel shall prevent the occurrence of errors in the calculation of protection settings. The dispatcher should issue the correct instruction to switch the operation mode under the condition that the grid operation mode and the protection setting value are correctly corresponded, and timely read the on-site protection setting value from the credit guarantee system and make a good proofreading.
6. Conclusion
When analyzing protection failure events, this paper comprehensively analyzes the entire process of the accident by combining multi-source information fusion technology and bow-tie model, clearly and intuitively explains the relationship between the cause and consequence of the risk model. This method lays the foundation for the safety assessment of protection failure events, and engineers can use this model to formulate prevention methods and risk mitigation measures. After that, the load loss and the corresponding economic loss are calculated as the basis for the risk assessment of protection importance, thereby determining the verification sequence of the online verification of relay protection. This new method based on the ranking of protection importance improves the defect of random blind sequencing in traditional verification, can more effectively perform the "four characteristics" verification of relay protection, and has a positive impact on maintaining the safe and stable operation of the power grid.

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