Fault Risk Assessment of Transmission Equipment Based on Condition Monitoring

Zhi-long XU¹, Yu-wei SUN¹, Jian-bao ZHU¹, Chao YE¹, Yu CHEN¹ and Zhong-yi WANG²,*

¹State Grid Nantong Power Supply Company, 226006, Nantong, China
²School of Energy and Electrical Engineering, Hohai University, Nanjing, China
*Corresponding author

Keywords: Power transmission equipment, Condition monitoring, Importance, Fault risk assessment, Maintenance strategy.

Abstract. This paper evaluates the risk of transmission equipment fault combined with the safety of transmission equipment based on condition monitoring. First of all, the monitoring system monitors important parameters related to the environment, electricity, and machinery in the operation of the power transmission equipment to determine the operating status of the power transmission equipment. Secondly, the impact of transmission equipment on power system risks is reflected by risk indicator. The proposed risk indicator combines the probability of transmission equipment failure and the importance of the equipment. Finally, a reliable and safe maintenance method is determined while taking into account the operating status (reliability) of the transmission equipment and the impact (importance) of the equipment on the system. This method can more reasonably allocate maintenance resources and improve the reliability and safety of power system operation.

Introduction

Power transmission equipment is the key to the operation of the power system, because there are a large number of power transmission equipment in a system. And their characteristics are different (age, failure probability, impact of failure), so their maintenance methods are very complicated. When formulate a transmission equipment maintenance strategy, not only the operation status of the transmission equipment itself, but also the impact of the transmission equipment outage on the system should be considered.

The operation status of the transmission equipment should be evaluated and analyzed according to the selected condition monitoring parameters. This method uses state monitoring parameters to evaluate the overall state of the power transmission equipment and estimate the probability of the fault status of the power transmission equipment, and propose a comprehensive maintenance decision combining the operating status (reliability) of transmission equipment and the impact of equipment on the system (safety). The purpose of this method is to reduce the risk of power system operation. According to the maintenance decision index, the power transmission equipment is divided into normal status, timely maintenance, emergency maintenance and replacement maintenance.

The rest of the paper is organized as follows. Section II discusses the methods for risk assessment. Section III introduces the state recognition technology of transmission equipment. The section IV analyzes the failure probability of transmission equipment, and proposes a risk assessment model of transmission equipment combined with importance. Section V introduces the maintenance strategies for transmission equipment. An example analysis is performed in Section VI. The last part gives the conclusion.

Risk Assessment Method for Transmission Equipment

In the past few decades, power system risk assessment and management has been widely used in
almost every level of power systems, namely power generation, transmission and distribution systems [1].

As shown in figure 1, power system risk assessment usually involves general steps. (1) The first step is to monitor the condition of important components of the power transmission equipment and collect monitoring data. Because the state monitoring data of power transmission equipment come from various sources, in order to make data reflect different states directly, status data requires signal processing. (2) In the second step, the processed monitoring parameters are compared with the allowable values of the parameters to evaluate the status of the transmission equipment, and the working status (fault) of the transmission equipment is determined. (3) The third step uses the associated components to determine the failure probability of the transmission equipment, and at the same time to assess the consequences of each failure event. (4) The fourth step, the risk index associated with each failure event can be calculated by the product of the failure probability (reliability) and the failure consequence (safety). (5) Finally, the corresponding maintenance strategy is developed according to the risk index. The risk index calculation formula is shown in Eq. 1

\[ R(E_i) = P(E_i) \cdot C(E_i) \]  

where \( C(E_i) \) represents the consequence of the failure event, \( P(E_i) \) represents the probability of the failure event, \( R(E_i) \) represents the failure event risk index.

Figure 1. Risk assessment of transmission equipment based on condition monitoring.

**Power Transmission Equipment Status Recognition**

The process of monitoring the status of power transmission equipment is to identify whether the status of the power transmission equipment is normal, timely discover and determine the nature and location of the fault, determine the development trend of the fault. During the operation of power transmission equipment, signals such as temperature, pressure, current, voltage, vibration, and energy will inevitably be generated during the operation of power transmission equipment. According to different status monitoring requirements, different signals can be selected to indicate the status of power transmission equipment. The system monitors several key parameters of the transmission equipment operation, finds potential failures, and judges the operation status of the transmission equipment. These parameters may be related to the environment in which the transmission equipment is located, mechanical wear, gas density, and electrical quantities during operation. In the power transmission equipment monitoring technology, some sensors are used, such as pressure sensors, fiber optic sensors, etc., in combination with microprocessors to perform monitoring tasks.

The signal processing and comparison process of power transmission equipment mainly extracts the monitoring parameters related to the fault from the monitoring signals, and compares the monitoring parameter signals with the allowed parameter values to determine whether the parameters are within the allowed range. By analyzing the monitoring parameter signals, the parameter signals of the equipment are extracted and are used to identify equipment failures based on signals and discrimination criteria. Once the equipment deviates from the normal operating state, it is necessary to
further analyze the cause of the failure and provide a reasonable maintenance strategy based on the actual operating conditions.

**Risk Assessment of Transmission Equipment Based on Importance**

The first method to study the failure rate of transmission equipment is based on the bathtub curve and the Weibull distribution, and calculate the failure rate of the equipment\[^2,3\]. The second method is to study the relationship between equipment health and equipment failure rate after defining the health of the equipment\[^4\]. Such as the EA formula:

\[
P(X) = K \times e^{-C \times X} \tag{2}
\]

where \(X\) is the state health of the equipment, \(K\) is the proportionality factor, \(C\) is the curvature coefficient, and \(P\) is the probability of failure.

Each fault event in the transmission system can be analyzed from the perspective of the impact of the fault, so that the impact of the fault is quantified, and the results may include cost, reliability, safety, stability, and importance. When formulate a maintenance strategy for transmission equipment operating in the power system, not only the operating conditions of the transmission equipment, but also the safety of the transmission equipment in the power system should be considered.

The safety of power transmission equipment can be translated into the importance of the equipment. The importance of transmission equipment is how much the equipment will affect the system after a fault. The higher the importance of the equipment, the equipment may be in an unsafe operating state even if minor faults occurs. Equipment is less important, and equipment is in a more secure state. Different standard maintenance strategies are developed based on the importance of the equipment. Transmission equipment with high importance in the system are developed high maintenance standards, and transmission equipment with low importance in the system are developed appropriate maintenance standards. Power system equipment should be maintained and operated under certain importance constraints, and any violation of these constraints will have an adverse impact.

### Table 1. Equipment importance degree division diagram.

| Equipment types          | Equipment condition                                                                 |
|--------------------------|--------------------------------------------------------------------------------------|
| Key equipment            | (1) In the normal operation mode, equipment failure may cause one or more electric safety accidents.  
(2) Power equipment worth 10 million or more.  
(3) A device failure will directly cause a power interruption to a critically important user. |
| Important equipment      | (1) In normal operation mode, equipment failure may cause a level 1 power safety event.  
(2) Power equipment worth 8-10 million  
(3) Equipment failure will directly trigger the interruption of power supply to the first-level important users. |
| Concerned equipment      | (1) In normal operation mode, equipment failure may cause two or three power safety times.  
(2) Power equipment worth 5-8 million  
(3) Equipment failure will directly trigger the interruption of power supply to the second-level important users. |
| General equipment        | Equipment other than the above equipment                                           |

A maintenance plan is developed by combining the probability of equipment failure with the importance of the equipment. Risk index for power transmission equipment in shown in Eq.3.

\[
R(E_i) = P(E_i) \cdot I(E_i) \tag{3}
\]

where \(P(E_i)\) is the probability of an abnormality in the power transmission equipment. \(I(E_i)\) is the importance index of the power transmission equipment in the system. \(R(E_i)\) is the power transmission equipment risk index, which can indicate the degree of influence of the power transmission
equipment on the system risk in this state. All identified events calculate the results according to Eq.3. The risk of fault is calculated by multiplying the probability of failure event and the importance [5]. Events can be sorted based on these risk factors.

**Maintenance Strategy of Transmission Equipment**

In order to determine if the power transmission equipment is sufficient for switching operations for reconfiguration, a maintenance strategy is designed for the entire system, as shown in Figure 2.

The strategy diagram is divided into 16 areas based on equipment strategy risk. When an equipment determines the risk of failure, the equipment can correspond to a area in the strategy diagram. The vertical axis represents the equipment failure rate, and the horizontal axis represents the importance of the equipment. The equipment’s importance are normalized to between 0 and 100, where 0 means the equipment has the lowest importance and 100 means the equipment is the most important. The position close to the area 4 indicates that the state of the equipment is good and the degree of influence on the system is not high. When making maintenance decisions, the equipment falling into this part of the area is not repaired. The location close to area 7 indicates that attention to the importance and failure of the equipment needs increase, and timely maintenance are required. Close to area 10 indicates that the equipment's own condition and importance are poor, and emergency maintenance are required. The proximity to area 13 indicates that the equipment is very important and in poor condition. The equipment may be in an unsafe and unreliable operating state and may require replacement maintenance. Different areas correspond to different maintenance strategies.

**Example Analysis**

An 110kV substation is taken as example in Figure 3. There are multiple transmission equipment in the substation. Due to different installation times and different loads, the status of each transmission equipment is different. Different transmission equipment locations have different failure rates, and the impact of transmission equipment on the system is different. 5 circuit breakers CB # 3, CB # 8, CB # 10, CB # 16 and CB # 19, one transformer T # 1, two isolation switches D # 1 and D # 2, two transmission lines L # 1 and L # 2 are selected from the substation as examples.
First, the state of the equipment is evaluated based on the monitoring data of the equipment, and the probability of failure of each equipment is calculated. Equipment with a failure rate greater than 0.2 need to be considered for maintenance. Then, based on the importance index I of the equipment, the fault risk of the equipment is calculated and maintenance evaluation on the equipment is performed.

| Numbering | Failure rate | Importance | Risk of failure | Maintenance strategy |
|-----------|--------------|------------|-----------------|---------------------|
| D#1       | 0.55         | 76         | 41.8            | replacement maintenance |
| CB#3      | 0.81         | 70         | 56.7            | replacement maintenance |
| CB#19     | 0.38         | 49         | 18.62           | Timely maintenance |
| T#2       | 0.04         | 70         | 2.8             | Normal status |
| L#1       | 0.000477     | 39         | 0.018603        | Normal status |
| CB#10     | 0.63         | 40         | 25.2            | Emergency maintenance |
| CB#8      | 0.52         | 55         | 28.6            | Emergency maintenance |
| L#2       | 0.000414     | 30         | 0.01242         | Normal status |
| CB#16     | 0.42         | 42         | 17.64           | Timely maintenance |
| D#2       | 0.00439      | 46         | 0.20194         | Normal status |

Among them, CB # 16 and CB # 19 should be timely maintained. CB # 3 has a very high failure rate and high importance. It is in an unsafe and unreliable operating state, indicating that failure of power transmission equipment will cause a very large risk to the system and requires replacement. Although D # 1’s failure rate is relatively low, it has high importance. It is in a reliable and unsafe operating state. Its failure will also cause a very large risk to the system, which requires emergency maintenance or even replacement maintenance. CB # 8 and CB # 10 have high failure rates, and their operating conditions are relatively poor. Although the risk to the system is not large, emergency maintenance is also required. Other devices are in a normal state. The distribution diagram of the selected transmission equipment maintenance strategy is shown in Figure 4. From this figure, the selected maintenance strategy of the transmission equipment can be seen.

Isolation switch D # 1, circuit breaker CB # 3 must be replaced for maintenance. The circuit breakers CB # 8 and CB # 10 need emergency maintenance, and the circuit breakers CB # 16 and CB # 19 need timely maintenance. According to the maintenance indicators, maintenance is performed in the order of CB # 3, D # 1, CB # 8, CB # 10, CB # 16, and CB # 19.
Summary

The method uses condition monitoring to monitor the electrical parameters and non-electrical parameters of the equipment, and judges the operating status and failure rate of the equipment. Based on the power system risk assessment model, the method makes a quantitative assessment of the impact of transmission equipment on the risk of the power system, and proposes the risk index of the transmission equipment in the system. Guided by the reliability and safety of transmission equipment, a framework based on the probability and importance of transmission equipment failure was designed to determine comprehensive maintenance indicators for transmission equipment risks. This method can classify the power transmission equipment into normal state, timely maintenance, emergency maintenance and replacement maintenance according to the power transmission equipment maintenance index.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (51837004) and the “111” project (B14022)

References

[1] Lie. Risk Assessment of Power Systems: Models, Methods, and Applications, J. John Wiley and Sons, Canada, 2005.

[2] WenYuan Li. Evaluating mean life of power system equipment with limited end-of-life failure data, J. IEEE Transactions on Power Systems, 2004, 19(1): 236-242.

[3] Wenyuan Li, Vaahedi, Choudhury P. Power system equipment ageing, J. IEEE Power and Energy Magazine, 2006, 4(3): 52-58.

[4] Ruijin Liao, Feilong Huang, Lijun Yang. Unascertained Rational Number Method for Calculating Transformer State Evaluation Index Weights, J. High voltage technology.2010, 36(9):2219-2224.
[5] Natti, Kezunovic. A Risk-Based Decision Approach for Maintenance Scheduling Strategies for Transmission System Equipment, J. 10th International Conference on Probabilistic Methods Applied to Power Systems, Singapore. May 2008.

[6] Jiirgen, Schlabbach, Torsten Berka. Reliability-Centered Maintenance of MV Circuit-Breakers, J. 2001 IEEE Porto Power Tech Conference 10th-13th September, Porto, Portugal.

[7] Tommie Lindquist, Lina Bertling and Roland Eriksson. A Feasibility Study for Probabilistic Modeling of Aging in Circuit Breakers for Maintenance Optimization, J. 8th International Conference on Probabilistic Methods Applied to Power Systems, September 12-16, 2004.

[8] Payman Dehghanian, Mladen Kezunovic, Gurunath Gurrala. Security-Based Circuit Breaker Maintenance Management, J. 2013 IEEE.

[9] Dabo Zhang, Yigang He. Preventive maintenance decision of circuit breaker based on condition monitoring and substation risk, J. Journal of Electric Power Science and Technology, 2014, Vol. 29.