Fault Analysis of Transmission Equipment Based on Condition Monitoring

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Abstract. This paper proposes a method for evaluating the operating status and reliability of power transmission equipment in power systems. First, by analyzing the aging factors, common faults, and major faulty components of the main transmission equipment, the main condition monitoring parameters of each transmission equipment are determined. Then, the key parameters such as the environment, machinery, and electricity of the transmission equipment are monitored to obtain the operating status data of the transmission equipment, and fault limits and alarm limits are set to determine the operating status of the transmission equipment. Finally, a health index for monitoring parameters and a comprehensive health index for transmission equipment are proposed. This method has a wider scope of application and a more specific analysis process than previous methods, which is conducive to analyzing the working status of power transmission equipment and improving the reliability and safety of normal operation of the power system.

Introduction

The operating status of power equipment is closely related to the safety and reliability of the power system. Failure of power equipment will cause local or large-scale power outages and result the entire power system in an unsafe operating state. Therefore, it is necessary to adopt reasonable maintenance strategies for power equipment, timely discover and solve problems in the operation of power equipment, and ensure that the system can supply power safely and reliably.

The accuracy and reliability of the judgment method of fault diagnosis will directly affect the normal operation and maintenance of power transmission equipment, and even affect the safety and reliable operation of the entire power system. With the application of a large number of sensing technologies and intelligent terminal equipment, a fault diagnosis method for power transmission equipment based on condition monitoring is one of the effective means to improve the efficiency of equipment condition maintenance and improve the ability of fault discrimination.

This paper proposes a method for measuring fault conditions of power transmission equipment based on condition monitoring data. This method determines the status of the power transmission equipment by analyzing the common fault types of the power transmission equipment. Based on the study of the environmental, electrical, and mechanical condition monitoring parameters of the transmission equipment, the corresponding relationship between the monitoring parameters and the fault is established. This paper is organized as follows. The second II analyzes the transmission equipment, and analyzes the main aging factors and fault types of the transmission equipment. The section III introduces the process of condition monitoring of transmission equipment and the transmission equipment condition monitoring technology and the main monitoring parameters of transmission equipment. The section IV takes the SF6 circuit breaker as an example to establish a state assessment model and a health index. Section V analyzes the example and finally gives the conclusion.
Analysis of Transmission Equipment

Reliability Analysis of Transmission Equipment

In the operation of power transmission equipment, aging is mainly caused by aging of insulation equipment \([1-4]\). The main influencing factors are \([4,5]\): high temperature, voltage, mechanical wear, dust and other environmental factors.

- High temperature factors: Temperature rise of insulation materials leads to deterioration and aging of insulation materials.
- Voltage factor: When the applied electric field reaches the initial discharge voltage of the air gap, a partial discharge will occur, which will damage the insulation.
- Mechanical wear factors: Vibration caused by mechanical action can cause damage and wear to welding points and operating mechanisms in equipment structures.

Analysis of Fault Types of Transmission Equipment

Transformer fault: transformer internal faults, external short circuit faults causing transformer winding damage, open windings, damp discharge of transformer main insulation, etc.

- High voltage circuit breaker fault: Opening and closing fault, malfunction and refusal fault, insulation fault, current-carrying fault, leakage fault.
- Isolation switch fault: Corrosion of switches, contact overheating, and fault of porcelain pillars.
- Capacitor and reactor fault: Fault caused by missing insulation medium, over-voltage fault and over-current fault, discharge fault, capacitor three-phase current imbalance.
- Transmission line fault: Short circuit to ground, disconnection fault, overheating of the line.

Monitoring Method of Power Transmission Equipment

Figure 1 shows the flow chart of power transmission equipment monitoring. The condition monitoring process of power transmission equipment is: (1) The first step is to analyze the monitored transmission equipment, and analyze the major fault types of the equipment, the major components of the fault and the main parameters involved in the fault, and determine the monitoring parameters of the equipment. (2) The second step is to monitor and collect the main fault parameters of the equipment and process the parameters. (3) The third step uses the threshold method to set the parameter's fault limit and alarm limit, and compare the collected parameters with the limits, and make a preliminary judgment of the operating status of the equipment. (4) The fourth step is to calculate the health index of the equipment, and determine the operating trend of the equipment and the necessary maintenance measures.

![Power transmission equipment status monitoring flow chart](image)

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.

Table 1 lists several transmission equipment and signals that need to be monitored. Once a parameter exceeds the limit, the monitoring system will generate an alarm.

| Equipment                        | Monitoring Parameters                                                                 |
|----------------------------------|----------------------------------------------------------------------------------------|
| Capacitive insulation equipment  | Dielectric loss tangent, capacitance and current                                         |
| Lightning arrester               | Resistive current in total current                                                      |
| Cable                            | Dielectric loss tangent, capacitance and current                                         |
| Transformer                      | Dissolved gas content                                                                  |
| High voltage circuit breaker      | Temperature, air pressure, opening and closing coil current, mechanical vibration, contact response time and speed |

**State Monitoring Model of Transmission Equipment**

**Condition Monitoring Modeling Method**

The paper supposes the vector $X_m$ (m=1, 2,...) reflects a monitored parameter over time (m is the number of monitored inputs). If a value reaches the fault limit in any equipment operation, it is called the fault limit $F_m$. Alarm limits are set with upper and lower limits $A_m^{\text{max}}$ and $A_m^{\text{min}}$. The vector $D_m$ is the difference between the fault limit and the alarm limit [7]:

$$D_m^{\text{max}} = F_m^{\text{max}} - A_m^{\text{max}}, m = 1, 2, ..., k$$

$$D_m^{\text{min}} = A_m^{\text{min}} - F_m^{\text{min}}, m = 1, 2, ..., k$$

In order to determine whether the equipment operates safely and reliably, the parameter threshold map of the monitored equipment is designed as shown in Figure 2. If the main parameter value of the monitored equipment does not exceed the alarm limit and is located in area 1, the equipment is safe and reliable. If the monitored parameter value exceeds the alarm limit and does not exceed the fault limit, the device is located in area 2, indicating that the monitored device may be in an alarm state. If the monitored parameter value exceeds the fault limit and is located in area 3, it means that the monitored equipment is in a fault state and is not safe and reliable.

![Figure 2. Threshold map of monitored transmission equipment parameters.](image)

$V_{X_m}$ is the value where $X_m$ exceeds the upper and lower alarm limits. When the vector $X_m$ exceeds the fault limit, the corresponding $V_{X_m}$ is considered a fault.
\[ V_{x_m}^{\max} = X_m - A_{m}^{\max}, \text{if } X_m > A_{m}^{\max} \]  
(3)

\[ V_{x_m}^{\min} = A_{m}^{\min} - X_m, \text{if } X_m < A_{m}^{\max} \]  
(4)

\[ V_{x_m} = 0, \text{if } A_{m}^{\min} < X_m < A_{m}^{\max} \]  
(5)

when \( X_m \) exceeds the alarm limit but does not exceed the fault limit, the vector \( V_{x_m} \) lies within the threshold range. When \( X_m \) is within the required alarm limit, its value is zero.

**Condition Assessment Model**

Four \( SF_6 \) circuit breakers CB # 1, CB # 2, CB # 3, CB # 4 are selected as examples. The selected circuit breakers are divided into reactor breaker, bus bar breaker, transformer breaker and line breaker according to the installation position and function. The main fault components of these circuit breakers and the parameters that need to be monitored are analyzed. The characteristics of the selected circuit breaker are shown in Table 2. Table 3 shows the main monitoring parameters and their upper and lower limits for fault and alarm limits.

### Table 2. Selected Circuit Breaker Feature.

| Circuit breaker type  | Major faulty parts                        | Main monitoring parameters                           |
|-----------------------|-------------------------------------------|------------------------------------------------------|
| CB#1 Reactor breaker  | Contacts, Trip latch mech, Auxiliary contacts | Temperature, Opening and Closing coil current, Opening and closing speed and time, Pressure |
| CB#2 Line breaker     | Trip latch mech, Incomplete switch         | Opening and Closing time, Pressure, Mechanical vibration, Mechanical travel |
| CB#3 Transformer breaker | Incomplete switch                        | Mechanical vibration, Mechanical travel |
| CB#4 Bus bar breaker  | Trip latch mech, Auxiliary contacts, Other machinery | Opening and Closing time and speed, pressure, Temperature, Mechanical vibration |

### Table 3. Minimum and Maximum Limits for Alarm and Fault Conditions during Circuit Breakers Closing Operation.

| Monitoring parameters | \( A_{m}^{\min} \) | \( A_{m}^{\max} \) | \( F_{m}^{\min} \) | \( F_{m}^{\max} \) |
|-----------------------|------------------|------------------|------------------|------------------|
| Temperature (°C)      | -20              | 90               | -30              | 100              |
| \( SF_6 \) gas pressure (psig) | 72               | 89               | 66               | 95               |
| Closing speed (m/s)   | 3.5              | 5.0              | 3.0              | 5.5              |
| Mechanical closing time (ms) | 52               | 71               | 47               | 76               |
| Mechanical travel time (ms) | 195              | 208              | 190              | 213              |
| Vibration signal (m/s^2) | -75             | 75               | -100             | 100              |
| Opening current (mA)  | 1100             | 2000             | 1000             | 2100             |
| Closing current (mA)  | 1400             | 2000             | 1300             | 2100             |

In order to monitor the change in circuit breaker pressure over time, it is assumed that the required pressure value is expressed as \( P_i^d \). The upper and lower alarm limits and fault limits of the circuit breaker are expressed as \( A_{P_i}^{\max} \), \( A_{P_i}^{\min} \), \( F_{P_i}^{\max} \), \( F_{P_i}^{\min} \). The pressure exceeding the alarm limit is defined as follows [8]:

\[ V_{P_i}^{\max} = [P_i - A_{P_i}^{\max}] / P_i^d, \text{if } P_i > A_{P_i}^{\max} \]  
(6)
\[ V_p^{\min} = \left[ A_p^{\min} - P_i \right] / P_i^{d}, \text{if } P_i < A_p^{\min} \]  
(7)

\[ V_p^{\min} = 0, \text{if } A_p^{\min} < P_i < A_p^{\min} \]  
(8)

To determine the pressure health index of the circuit breaker, the vector is converted into a scalar health index. The difference between the pressure’s fault limit and the alarm limit is defined as

\[ D_i^{\max} = \left[ F_i^{\max} - A_i^{\max} \right] / P_i^{d} \]  
(10)

\[ D_i^{\min} = \left[ A_i^{\min} - F_i^{\min} \right] / P_i^{d} \]  
(11)

The circuit breaker pressure health index is obtained.

\[ HI_p = 1 - \left[ \left( V_i^{\max} / D_i^{\max} \right)^{2n} + \left( V_i^{\min} / D_i^{\min} \right)^{2n} \right]^{1/2n} \]  
(12)

The equation shows that from the point of view of monitoring pressure, the equipment is healthy when \( HI_p = 1 \) and there are some faults when \( HI_p < 0 \). For values between the 0 and 1 limits, the equipment is identified as being in an alarm state. The health index trend corresponding to each parameter will indicate the equipment’s working condition and health level in this parameter.

In order to evaluate the overall health indicators of the circuit breaker, the health indicators are combined with various monitoring signals. The circuit breaker’s comprehensive health index will indicate the overall health and reliability of the circuit breaker.

\[ CHI = \frac{\sum_{i=1}^{m} \left( 1 - \left[ \left( V_i^{\max} / D_i^{\max} \right)^{2n} + \left( V_i^{\min} / D_i^{\min} \right)^{2n} \right]^{1/2n} \right)}{m} \]  
(13)

\( CHI \) is the comprehensive health index of the equipment. The trend of the index can be determined as a reliable indicator of the health of the circuit breaker. If the index is rising, it indicates that the circuit breaker is unreliable or needs to be repaired. Otherwise, the circuit breaker is considered healthy.

**Example Analysis**

Using the data provided in Table 3, combined with the parameters for different circuit breakers in Table 2, the difference between the alarm limit and fault limit (\( D_m^{\max}, D_m^{\min} \)) and the required value (\( P_i^{d} \)) are calculated in Table 4.

| Monitoring parameters(CB#1) | \( P_i^{d} \) | \( D_m^{\min} \) | \( D_m^{\max} \) | Monitoring parameters(CB#2) | \( P_i^{d} \) | \( D_m^{\min} \) | \( D_m^{\max} \) |
|-----------------------------|--------------|-----------------|-----------------|-----------------------------|--------------|-----------------|-----------------|
| Temperature (°C)            | 35           | 10              | 10              | Vibration signal (m/s²)     | 30           | 25              | 25              |
| Opening current (mA)        | 1500         | 100             | 100             | Mechanical closing time (ms) | 52           | 5               | 5               |
| Closing current (mA)        | 1800         | 100             | 100             | SF₆ gas pressure (psig)      | 72           | 6               | 6               |
| Closing speed (m/s)         | 4.3          | 0.5             | 0.5             | Mechanical travel time (ms)  | 195          | 5               | 5               |
| Mechanical closing time (ms)| 62           | 5               | 5               | SF₆ gas pressure (psig)      | 82           | 6               | 6               |
| Monitoring parameters(CB#3) | \( P_i^{d} \) | \( D_m^{\min} \) | \( D_m^{\max} \) | Monitoring parameters(CB#4) | \( P_i^{d} \) | \( D_m^{\min} \) | \( D_m^{\max} \) |
| Mechanical travel time (ms) | 195          | 5               | 5               | Vibration signal (m/s²)     | 30           | 25              | 25              |
| Vibration signal (m/s²)     | 30           | 25              | 25              | Mechanical closing time (ms) | 52           | 5               | 5               |
Using the information in Table 3 and 4 to calculate the health index of CB over time and the input of new monitoring parameters. The health indexes of the monitoring parameters of the four circuit breakers are shown in Figure 3. Figure 4 also shows the overall health index of the four circuit breakers over time and the input of new monitoring parameters.

The analysis of the circuit breaker CB # 1 in Figure 3 shows that the temperature signal state of the circuit breaker is unreliable because remains negative. The monitored pressure signal was reliable. The health index of the last three monitoring signals shows a downward trend, is often in an alarm state, and is not reliable. The unhealthy condition of temperature will be converted into the comprehensive health index of the circuit breaker, making it overall unreliable and unsafe operating state. Figure 3 shows that the air pressure, mechanical closing time, and mechanical stroke of CB # 2 are reliable, and the mechanical vibration is in an abnormal state.

| Parameter                        | CB#1 | CB#2 | CB#3 | CB#4 |
|----------------------------------|------|------|------|------|
| SF6 gas pressure (psig)          | 72   | 6    | 6    | 6    |
| Closing speed (m/s)              | 4.3  | 0.5  | 0.5  | 0.5  |
| Temperature (°C)                 | 35   | 10   | 10   | 10   |

![Figure 3. Trend of health index of CB monitoring parameters.](image1)

![Figure 4. Trends in the comprehensive health index of several circuit breaker.](image2)

In Figure 4, the comprehensive health index of CB # 2 is less than 1, and CB # 2 is in an alarm state. CB # 3 is in safe operation. The mechanical closing time and closing speed of CB # 4 are abnormal, and the whole is in an alarm state.
Summary

The proposed fault analysis method based on the condition monitoring of the power transmission equipment in this paper relates to state parameters of the power transmission equipment of the Electricity and non-electricity aspects. It provides a quantitative method for analyzing the critical parameters and the state of the power transmission equipment in real time. It can perform an evaluation of the power transmission equipment to determine the operating state of the power transmission equipment (health, alarm or fault) and help improve the reliability and stability of the normal operation of the system.

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