Design of remote operation and maintenance platform of substation DC system for field defect handling

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Abstract. The current remote operation and maintenance platform of substation DC system mainly relies on manual use of each independent monitoring device to collect and transmit data for remote operation and maintenance management, which is difficult to realize intelligent operation of substation and also leads to slow response and poor processing performance of operation and maintenance platform. In order to optimize the above-mentioned problems, the remote operation and maintenance platform of substation DC system for on-site defect processing is studied and designed. Based on the framework of the operation and maintenance platform, a combination of balanced and unbalanced bridge-based principle is used to monitor the DC insulation status. The JSON protocol is used to realize the data interaction between the operation and maintenance platform and the management terminals, and to design the DC system defect processing scheme. The Floyd shortest path algorithm is used to plan the operation and maintenance inspection strategy of the platform to achieve fast operation and maintenance of the DC system. The platform performance test results show that the performance index of the designed operation and maintenance platform is significantly improved, and the average request response time is shortened by 28.1%, and the operation and maintenance management effect is better.

1. Introduction

When the AC power supply of the substation stops due to power failure, the battery bank in the DC system will continue to supply DC power to the system as a backup power source to ensure the normal operation of the secondary system. The main components of the DC system are: AC distribution module, charging module, battery bank, step-down device, DC busbar, and centralized monitoring module [1]. The functions of each module are combined to enable effective management of the substation DC system. The vast majority of foreign DC power remote monitoring platforms use the original control system of the DC power system, which can avoid major accidents by analyzing and processing the collected real-time data and pre-diagnosing the DC power supply, alerting and notifying maintenance personnel for maintenance before possible accidents occur [2]. The literature [3] uses GPS positioning function embedded in a PDA to locate and collect data from DC system equipment in a substation, and this platform is limited by hardware accuracy, resulting in low sensitivity of insulation detection. The literature [4] uses KVM system to realize the unified management of multiple systems in substations. The existing operation and maintenance platform is in template for defect management of related equipment and relies heavily on manual work, which
affects the operation and maintenance efficiency and also makes it difficult to ensure the reliability of DC system operation. Therefore, in order to improve the management efficiency of substation DC system and realize intelligent remote monitoring of DC system working status, this paper will design a remote operation and maintenance platform for field defect handling of substation DC system and verify the feasibility of this platform.

2. Design of remote operation and maintenance platform of substation DC system for field defect handling

2.1. Substation DC system remote operation and maintenance platform framework construction

DC system provides power for substation control load and important DC power load. As a DC power remote monitoring and maintenance system, it should be able to meet the demand of DC system for each voltage level (configured with single or two batteries) of substation, and is applicable to single battery of each voltage level such as 2V, 3.2V, 6V and 12V [5]. The framework of the DC system remote operation and maintenance platform designed in this paper is shown in figure 1 below.

2.2. DC system insulation monitoring

The remote operation and maintenance platform designed in this paper uses the principle based on the combination of balanced bridge and unbalanced bridge for DC insulation status monitoring. Only the balanced bridge works when the system is normal, and the unbalanced bridge works only once when the balanced ground is monitored, and the bus-to-ground voltage fluctuation rate caused by the unbalanced bridge start is less than ±5% [6]. The schematic diagram of the unbalanced bridge to detect the insulation condition of the DC system is shown in figure 2, where R3 and R4 are the insulation detection bridge resistors and K1 and K2 are the controllable switches [7].
The working process of the unbalance bridge is as follows: When the controllable switch K1 is closed and K2 is disconnected, the positive bus-to-ground voltage is measured as $U_{+}$, and the voltage of the negative bus to ground is $U_{-}$ [8]. When the controllable switch K1 is disconnected and K2 is closed, the positive bus-to-ground voltage is measured as $U_{+}$, and the negative bus-to-ground voltage is $U_{-}$. The measured voltage of the positive bus to ground is $U_{+}$, and the voltage of the negative bus to ground is $U_{-}$. Let: the voltage between the positive and negative busbar is $U_{m}$, the balanced bridge resistance $R = R_{2} = R$, the unbalanced detection bridge resistance $R_{1} = R_{4} = R$, then according to the following formula can be obtained from the positive to ground resistance $R_{+}$ and negative to ground resistance $R_{-}$.

$$
R_{+} = \frac{RR_{1}(U_{2+} - U_{1+})}{-RU_{2-} - R_{1}(U_{2+} - U_{1+})}
$$

$$
R_{-} = \frac{RR_{4}(U_{2-} - U_{1+})}{-RU_{1-} - R_{4}(U_{2-} - U_{1+})}
$$

The magnitude of the insulation resistance can be calculated from the above equation to find the polarity where insulation degradation occurs and to judge the operation of that busbar insulation at the same time. Setting K1 and K2 as timed switching allows judgment of the simultaneous equal insulation degradation of both poles, and is therefore equally effective for symmetrical ground faults, making up for the lack of ground resistance measurement using a balanced bridge alone. For the sake of analysis, assuming that the negative insulation is normal and the positive insulation drops, the negative-to-ground voltage is.

$$
U_{-} = U_{m} \times \frac{R + R_{+}}{R + 2R_{+}}
$$

In the above equation, $U_{-}$ is the DC system negative-to-ground voltage; $R_{+}$ is the DC system positive-to-ground insulation resistance; $R$ is the DC insulation detection device balance bridge resistance. In order to ensure the safety of DC system, it is required $U_{-} < 0.55U_{m}$ . So the DC system positive-to-ground insulation resistance $R_{+}$ should meet $R_{+} > 4.5R$ . Based on the above design calculation, the single-arm test bridge is used to achieve the insulation detection of the DC system of the substation.

The single-arm detection bridge equipped with only negative single-arm detection bridge can ensure that the negative DC system voltage to ground is less than 50% of the DC bus voltage, which can reduce the fluctuation rate of the negative DC system bus voltage to ground. The voltage
fluctuation rate $\delta_w$ of the single-arm detection bridge can be calculated according to the following equation.

$$\delta_w = \frac{U_1 - U_2}{U_2}$$

(3)

In the single-arm detection bridge switching process, the DC positive to ground voltage is kept constant, so that the voltage fluctuation rate can be reduced by half on the basis of the above unbalance detection bridge voltage fluctuation rate control, so that the voltage fluctuation rate $\delta_w < 2.5\%$. The single-arm detection bridge can make the DC system achieve safe operating conditions to a certain extent. After the DC system insulation is tested using the single-arm detection bridge, the test data will be transferred to the monitoring end in accordance with the platform's remote data access requirements for real-time data observation by operation and maintenance personnel.

2.3. Realize remote operation and maintenance of substation DC system

The core idea of Floyd's shortest path algorithm is to gradually transform the initial matrix of weights into a shortest path matrix, which is implemented as follows. Assuming that there exists a directed or undirected graph $G = (V, E)$ with $N$ nodes, Floyd's algorithm requires defining two $N \times N$ matrices, denoted $D$ and $P$. Element $a[i][j]$ in matrix $D$ represents the distance from vertex $i$ to vertex $j$, while element $b[i][j]$ in matrix $P$ represents the vertices that pass in the middle from vertex $i$ to vertex $j$. In the initial state, matrix $D$ represents the distance between each vertex to each other vertex, called the weight, and if two vertices are not directly connected, the distance value between two points is infinity, while matrix $P$ in the initial state is the value of all elements $b[i][j]$.

For a substation DC system node, given a graph $G = (V, E)$, the set of vertices of the graph $G$ is $\{d_0, d_1, d_2, \ldots, d_{n-1}\}$, and the set of edges is $P(G) = \{p_0, p_1, p_2, \ldots, p_{n-1}\}$. According to the basic idea of Floyd's algorithm, its implementation steps are mainly divided into the following steps.

(1) The point distance matrix $D_0$ and the node matrix $P_0$ are constructed according to the algorithm idea, and the elements of the matrix are shown in the following equations (4) (5):

$$D_0[i][j] = \begin{cases} a_{ij}, & (d_i, d_j) \in E(G) \\ 0, & (d_i, d_j) \notin E(G), i = j \\ \infty, & (d_i, d_j) \notin E(G), i \neq j \end{cases}$$

(4)

$$P_0[i][j] = \begin{cases} c_{ij}, & (d_i, d_j) \in E(G) \\ 0, & (d_i, d_j) \notin E(G) \end{cases}$$

(5)

(2) Construct the iteration matrix $D_k$ of the point distance matrix $D_0$ and the iteration matrix $P_k$ of the node matrix. When the iteration node number $m$ increases from 1 to $h$, and $m \neq i, j$, when $D_{k-1}[i][m] \geq D_k[i][j]$ or $D_{k-1}[m][j] \geq D_k[i][j]$, it means that the current path length $D_{k-1}[i][j]$ will not be shorter after inserting node $d_m$ into the obtained path. Therefore, it is not necessary to calculate $D_{k-1}[i][m] + D_{k-1}[m][j]$. When $D_{k-1}[i][m] < D_k[i][j]$ and $D_{k-1}[m][j] < D_k[i][j]$,
$D_{i\rightarrow j}$ needs to be updated to the minimum of $D_{i\rightarrow j}$ and $D_{i\rightarrow m} + D_{m\rightarrow j}$, which is expressed as the shortest path between two points.

3) Terminate the algorithm when $D_k = D_{k+1}$; otherwise, repeat step (2).

According to the above algorithm to determine the operation and maintenance inspection path of the substation DC system remote operation and maintenance platform, it is able to mark the electronic map of the primary and secondary equipment of the intelligent substation, formulate the scattered distribution status of the equipment that needs attention for manual inspection or intelligent robot inspection, and realize the automatic generation of the inspection route through the computer program, simplify the workload of operation and maintenance personnel, shorten the inspection time, and thus improve the efficiency of operation and maintenance inspection. This completes the design of the remote operation and maintenance platform of substation DC system for on-site defect processing.

3. Experimental study

3.1. Test Overview

The experiment chose the comparison form that can visually show the platform performance, and the remote operation and maintenance platform designed in this paper was used as the experimental group, and the traditional DC system remote operation and maintenance platform was used as the comparison group. The test was conducted by testing the response to operation and maintenance work requests and the corresponding processing performance during the operation of the two remote operation and maintenance platforms, and comprehensively comparing the remote operation and maintenance platforms of the two groups. In order to ensure that the performance data of the final test is valid and reliable, the performance parameter standards of the DC system remote operation and maintenance platform are set as shown in table 1 below according to the relevant regulations.

| Number | Parameters               | Standard Description                                      |
|--------|--------------------------|----------------------------------------------------------|
| 1      | Throughput               | The amount of data transmitted per unit of time is not less than 1000tps |
| 2      | Packet forwarding rate   | No more than 0.1488 Mpps for 100 megabit networks        |
| 3      | Operation page response time | No more than 2s                                          |
| 4      | Business Success Rate    | 95~100%                                                  |
| 5      | CPU load                 | No more than 30%                                         |
| 6      | Average load             | No more than 15%                                         |
| 7      | Disk IO Utilization      | Not less than 400tps                                     |

The performance test of the operation and maintenance platform is divided into 3 groups, respectively, under the conditions of the number of concurrent users 10, 15, 20, each group of experiments for a total of 5 valid tests, take the average of each group of valid test data recorded. Analyze all the experimental index data during the test, and complete this platform performance comparison test results.

3.2. Platform test results and analysis

Table 2 below shows the data of the DC system remote operation and maintenance platform test for the experimental group and the comparison group, and the data in the table are analyzed to draw conclusions.
Table 2 Remote operation and maintenance platform test comparison data

| Test Parameters  | Experimental group | Comparison group |
|-----------------|--------------------|------------------|
|                 | Number of concurrent users | Number of concurrent users |
| Throughput/tps  | 10 15 20         | 10 15 20         |
|                 | 1230 1690 2180   | 1108 1340 1530   |
| CPU load/MB     | 157 235 290      | 185 268 379      |
| Average load/bps| 150 175 190      | 195 230 267      |
| Average response time/ms | 240 310 380 | 330 448 516 |

Analysis of the data in table 2 above shows that the test parameters of both groups of operation and maintenance platforms meet the set performance parameters, indicating that both operation and maintenance platforms can guarantee the basic substation operation requirements. The performance parameters of the experimental group operation and maintenance platform are significantly better than those of the comparison group operation and maintenance platform. From the viewpoint of response time, the response time growth rate of the experimental group platform is significantly smaller than that of the comparison group platform under the condition of different concurrent user requests. Numerically, the average response time of the experimental group platform is relatively shortened by about 28.1%.

4. Conclusion
The working power of protection devices, closing mechanisms, accident lighting and other loads in substations are provided by DC power systems. Remote operation and maintenance of DC systems in power systems can ensure safe and reliable operation of transmission and substation equipment in power systems. In this paper, we design a remote operation and maintenance platform for DC system of substation oriented to field defect processing, and verify the reliability of the platform through platform performance test experiments.

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