Experimental Study on Multi-Channel Positioning Technology of High Voltage Switchgear

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Abstract. This paper introduces the basic principle of high voltage switchgear discharge, expounds several common discharge types, and studies the precise localization of partial discharge of high voltage switchgear based on hyperboloid positioning method and space grid search method. The simulation test of the diagnostic process is used to test the feasibility of the above method. On the basis of precise positioning of the power supply, the local discharge power supply is simplified to a Gaussian current source, and the pulse parameters are calculated by the combination of the simulated annealing algorithm and the fdtd method. Evaluation. Simulation results show that the method of using multiple sensor measurements can accurately evaluate the equivalent pulse width $\tau$ and equivalent current amplitude $i_0$ of the simulated Gaussian pulse.

1. High voltage switchgear discharge principle

The failure of insulation of electrical equipment is mainly represented by the deterioration of insulation properties. The insulation of deterioration will appear to discharge under the effect of the electric field. Although these discharge phenomena occur between the electrodes, they are not serious enough to cause the insulation broken down. A partial discharge phenomenon is no discharge channel generated at the portion where the discharge is performed. However, with the passage of time, the insulation performance of electrical equipment will be deteriorated accumulatively by the cumulative effect of partial discharge, which will further expand the original insulation defects, eventually leading to severe consequences such as the collapse of the electrical equipment insulation system.[1]

Among the types of partial discharges that occur in high-voltage switchgear, the most common one is air-gap discharge. The presence of air bubbles is common in certain areas of liquid insulation and solid insulation. Figure 1 (a) shows the case where bubbles are present inside the solid or liquid insulation, the height of the entire insulating portion is $d$, and the bubble of height $\delta$ is at a position intermediate the two electrodes. Figure 1 (b) shows its equivalent circuit diagram, which can be used to study the mechanism of air gap discharge.

![Figure 1. Research mechanism of air gap discharge.](image-url)
As shown in Figure 1, a bubble exists inside the insulating medium, and the part is represented by the letter c. Its equivalent capacitance and resistance are represented by Cc and Rc, respectively; The bubble has an obvious series relationship, represented by the letter b, and its equivalent capacitance and resistance are represented by Cb and Rb respectively; the other parts of the medium are represented by the letter a, its equivalent capacitance and The resistances are represented by Ca and Ra, respectively.

When the voltage is applied to the insulator by the plate electrode, the following equation can be obtained from the circuit principle we have learned:

$$\frac{U_c}{U_b} = \frac{U_c}{U_b} = \frac{\omega C_b (1/R_b)^2 + (1/R_c)^2}{\omega C_c (1/R_c)^2} \approx \frac{\epsilon_b \delta}{\epsilon_c (d-\delta)}$$  \hspace{1cm} (1)

Where: $\epsilon_b$, $\epsilon_c$ are the relative dielectric constants corresponding to the b portion of the insulating medium and the portion c of the bubble, respectively.

When the electric field environment in which the insulator is located is an uneven electric field, the electric field can be decomposed by a vector, and is generally decomposed into a direction parallel to the surface of the insulator and perpendicular to the direction of the insulator. There are many influencing factors of creeping discharge, which have a great relationship with the environment of the insulating medium. Temperature, humidity, pollution degree, etc. may cause the surface electrical discharge of electrical equipment.[2] Installation conditions for high-voltage switchgear are generally poor, and dust, steam, smoke, and surface contamination are not negligible. Therefore, the high-voltage switchgear should be cleaned regularly to prevent the occurrence of creeping discharge and prolong the service life of the high-voltage switchgear.

The initial voltage of the corona discharge is primarily dependent on the positive and negative polarity of the high voltage conductor exposed to air or other gases. When the high voltage conductor is of a negative polarity and the high voltage conductor has a lower corona discharge starting voltage, the main reason for this is that the high voltage conductor easily emits electrons as a negative electrode. Therefore, when an alternating voltage is applied to a high voltage conductor exposed to air or other gases, the phase of the corona discharge phenomenon will always appear first in the negative half cycle, and the discharge pulse will assume a relatively neat shape, and will rarely occur in the positive half cycle. A discharge pulse appears.

2. Laboratory multi-channel positioning technology test

The laboratory simulates the multi-channel positioning detection technology of the high-voltage switchgear. This test mainly conducts the discharge test research by simulating the PD source.[3] The four-channel sensor transmits the discharge signal to the data collector by the processing, analysis and collection of the discharge signal. The discharge signal is systematically analyzed then conclude.[4]
In the three high-voltage switchgears next to each other, in order to facilitate the test analysis, they are named as switch cabinets a, b, and c. First, put the needle plate discharge model into the busbar chamber of the switchgear a, and place the three sensors A, B, and C, which are placed at a distance of about 80 cm in the horizontal direction on the front door of the three switchgear cabinets. 3.3. The position of the discharge source is judged by the time difference of the arrivals of the signal, and the test result is that the discharge source is located in the switch cabinet a or b. After that, the specific position of the PD source is narrowed down to the rectangular arrangement to the high voltage switch cabinet a. According to the time difference of the signals received by the four sensors, the PD source is finally determined. Busbar room. Finally, the four sensors are respectively attached to the four corners of the busbar room of the switchgear cabinet. The four-channel signal can be used to calculate the specific position of the PD source. The sensor 4 signals placed in the rectangular shape of the busbar chamber are shown in figure 2.

The spatial coordinates of the PD source and the sensor are shown in table 1. The energy method is used to determine the wave head time of the 4-way signal, and the measured arrival time difference of the obtained signal is shown in table 2.

Due to the limitation of the sampling rate of the high-speed acquisition card, the accuracy of the signal arrival time difference is not very high, so the positioning using the hyperboloid positioning method will generate a large error. For this situation, the grid sizes of 10 cm×10 cm×10 cm and 5 cm×5 cm×5 cm are selected respectively, and the spatial grid search method is used to locate the PD source. The calculation results are all \( P^*(x^*, y^*, z^*). \) = (10 cm, 40 cm, 30 cm) with an error of 35 cm. It can be concluded from the calculation results that the sampling rate of the high-speed acquisition card has a large interference to the accuracy of partial discharge positioning of the high-voltage switchgear. The results obtained through experiments show that the positioning technology still has certain performance problems and needs further changes and enhancements.

| Table 1. Experimental measurement of the spatial coordinates of the local discharge source and sensor. |
|---------------------------------------------------------------|
| Pd source Coordinate / cm | S1/cm | S2/cm | S3/cm | S4/cm |
| (45,21,42) | (0,0,0) | (72,0,0) | (0,0,114) | (72,0,114) |

| Table 2. Measured value of signal arrival time difference. |
|------------------------------------------------------------|
| Time difference | t12 | t13 | t14 |
| Signal arrival actual time difference / ns | 0.8 | 3.2 | 4.0 |

3. Simulation test of laboratory discharge power supply
By placing the power supply position, sensor position, and sensor receiving tev signal, the power supply pulse parameters can be evaluated to determine the actual discharge intensity. The simulation study is carried out in this paper. The basic principle of parameter evaluation usually simplifies the local discharge source to a Gaussian current source for evaluation. The ftdt calculation program is used, and the optimization method is used to optimize the partial discharge pulse parameters, ie, the equivalent current peak \( i_0 \) and the partial discharge pulse width \( \tau \). This is a solution to the electromagnetic inverse problem. Figure 3 is a schematic diagram of the Gaussian pulse source. When the receiving position of the sensor and the position of the discharge source are determined, the waveform of the signal received by
the sensor depends only on the equivalent pulse width $\tau$ of the local discharge source and the like. Effective amplitude $i_0$.

If $m$ transient electric field measurement sensors closely attached to the surface of the switchgear are used to monitor the electric field change on the surface of the switchgear, according to the $m$ electric field signal waveforms measured by the sensor, two unknown parameters $x=(x_1, x_2) = (\tau, i_0)$ = $(n\Delta t, i_0)$.

It can be estimated by minimizing the objective function as follows.

$$F = \sqrt{\frac{1}{m} \sum_{k=1}^{m} \left( \sum_{j=1}^{N} [E_k(j\Delta T, x) - E_{km}(j\Delta T)]^2 \right)} \Delta T$$

(2)

Where: $k$ is the number of the sensor; $N$ is the total number of discrete measurement points; $T$ is the duration of the signal measurement; $\Delta T$ is the time interval of the measurement; $E_k(j\Delta T)$ refers to the transient electric field signal calculated using the FDTD program at the same point as the $k$th sensor.

Figure 3. Pulse parameters of the discharge power.

4. Simulation test of laboratory annealing algorithm

In recent years, emerging non-heuristic global optimization algorithms solve complex problems by emulating and visualizing a natural phenomenon or process. When the decision variable $x$ is in a discrete state, the global optimization problem becomes a combinatorial optimization problem, which can be written as

$$\min F(x)$$

$$s \cdot t \cdot g(x) \geq 0, x \in D$$

(3)

Where: $x$ is the decision variable; $F(x)$ is the objective function; $g(x)$ is the constraint function; $D$ is the feasible domain consisting of a finite number of points.

Simulated Annealing (SA) evolved during physical annealing. Assuming that the decision variable is in the old state, when the external disturbance is received, the decision variable of the function changes from $x_{old}$ to $x_{new}$, and at the same time, the objective function of the system also changes from $F(x_{old})$ to $F(x_{new})$, the acceptance probability of the system changing from state $x_{old}$ to state $x_{new}$ is:

$$P = \begin{cases} 1, & F(x_{new}) < F(x_{old}) \\ \exp \left[ \frac{F(x_{old}) - F(x_{new})}{T} \right], & F(x_{new}) \geq F(x_{old}) \end{cases}$$

(4)

When $F(x_{new})<F(x_{old})$, the current state $x_{new}$ is an acceptable important state $x_{best}$; when $F(x_{new})\geq F(x_{old})$, if $\xi < p$, the current state $x_{new}$ is an acceptable important state $x_{best}$; if $\xi > p$, the current state is discarded $x_{new}$. The comparison between the simulated annealing algorithm and the physical annealing process is shown in table 3.
Table 3. The relationship between simulated annealing algorithm and physical annealing process.

| Simulated annealing algorithm | Physical annealing process |
|-------------------------------|---------------------------|
| solution                      | Molecular state           |
| Optimal solution              | Minimum energy state      |
| Control parameter initial value| High temperature dissolution|
| Metropolis criterion simulation| Isothermal process        |
| Control parameter drop        | Cooling process           |
| Objective function            | energy                    |

The iterative process of the canonical simulated annealing algorithm is as follows:

1. Arbitrarily select an initial value $x_i$ in the solution space, and let $i=0$, then the optimal solution $x_{best}=x_0$, the minimum system energy is $F(x_{best})$, determine initial temperature $t_i$;
2. If the internal circulation termination condition is reached at this temperature, turn to (6), otherwise turn to (3);
3. In the current optimal solution $x_{best}$, a new neighborhood solution $x_{new}$ is generated according to its neighborhood function, so that $\Delta F=F(x_{new})-F(x_{best})$;
4. If $\Delta F<0$, let $x_{best}=x_{new}$, $F(x_{best})=F(x_{new})$ turn to (2), otherwise generate between $[0,1]$ Random number $\xi$;
5. If $\exp (-\Delta F/t_i) < \xi$, turn to (3); otherwise, let $x_{best}=x_{new}$, $F(x_{best})=F(x_{new})$ turn (2);
6. Cool down, let $t_{i+1}=\text{update}(t_i)$, $i=i+1$, if the termination condition is satisfied, the algorithm ends, otherwise it turns to (3).

5. Evaluation of the power supply pulse parameters

The high-voltage switchgear partial discharge model is used for the simulation test. When using the measurement results of 4 sensors to evaluate the pulse parameters, it is assumed that 4 points $(50, 13, 109), (50, 49, 109), (50, 13)$ will be obtained from the front surface of the switchgear by simulation. $(50, 49, 13)$ is taken as the actual four electric field signals measured. Set a number of different true Gaussian pulse parameters $x^*=(\tau^*, I_0^*)=(n^*\Delta t, I_0^*)$, so that the initial value of the simulated annealing algorithm is $x_0=(\tau_0, 100) = (80\Delta t, 3)$, the search interval of the equivalent pulse width $\tau$ is set to $[20\Delta t, 300\Delta t]$, and the search interval of the equivalent amplitude $I_0$ is set to $[0.1, 20]$, optimized by The iterative iteration of the algorithm and the FDTD calculation program, when the algorithm terminates, the parameter value converges to the optimal solution $x=(\tau, I_0)=(n\Delta t, I_0)$.

Table 4 shows the optimization results of the partial discharge pulse parameters based on the 4-channel charged measurement results. It can be seen that the combination of the global optimized simulated annealing algorithm and the ftdt calculation program evaluates the maximum error of the equivalent pulse width $\tau$ of the Gaussian local discharge source to 0.2%. The maximum error of the equivalent amplitude $I_0$ is 3%. It can be seen from the calculation results that using multiple sensor measurements to evaluate the pulse parameters can obtain more accurate results.

Table 4. Optimal pulse parameters for monitoring partial discharge in four channels.

| condition     | True Gaussian pulse parameter | Optimize Gaussian pulse parameter |
|---------------|-------------------------------|----------------------------------|
| Pulse $\tau$ determinatio | $x^*=(\tau^*, I_0^*)=(n^*\Delta t, I_0^*)$ | $x^*=(\tau^*, I_0^*)=(n^*\Delta t, I_0^*)$ |
| $(60\Delta t, 0.5)$  | $(59.9\Delta t, 0.5)$        |                                  |
| $(60\Delta t, 1)$   | $(60\Delta t, 0.99)$         |                                  |
Amplitude $i_0$ is determined

| $n$          | $(60\Delta t,2)$   | $(59.9\Delta t,2)$ |
|--------------|---------------------|---------------------|
| Amplitude    | $(80\Delta t,1)$   | $(80\Delta t,0.97)$ |
| $i_0$        | $(100\Delta t,1)$  | $(99.8\Delta t,1)$  |
| determined   | $(120\Delta t,1)$  | $(119.9\Delta t,1)$ |

6. Conclusion

This paperly studies the precise localization of partial discharge of high voltage switchgear based on hyperboloid positioning method and space grid search method. The feasibility of the above method is verified by the simulation test of multi-channel electrification diagnosis process. On the basis of this, it is proposed to simplify the local discharge source to a Gaussian current source, and use the combination of simulated annealing algorithm and fdtd method to evaluate the pulse parameters. The simulation results show that the method of using multiple sensors can simulate Gaussian pulses. The effective pulse width $\tau$ and the equivalent current amplitude $i_0$ have a more accurate evaluation.

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