Research of PD transfer ratio analysis of converter transformer IPVD test based on distributed parameters

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Abstract. In the process of factory test of converter transformer, the withstand voltage test with partial discharge is usually used to judge whether the internal insulation structure is in good condition or not. If there is no partial discharge, the insulation is in good condition. There are tens of thousands of insulation materials in UHV converter transformer, and the winding structure is complex. If partial discharge is detected during the withstand voltage test, it is impossible to locate the discharge position quickly and accurately. In this study, by analysing the partial discharge signal transmission relationship in the withstand voltage test of converter transformer, combined with the partial discharge signal transmission model of converter transformer winding based on distributed parameters, the partial discharge area in the converter transformer winding is calculated and judged. This method can be applied to the IPVD test of converter transformer to assist in locating the partial discharge area in the winding, greatly shorten the time of fault diagnosis and location of converter transformer, and enhance the scientificity and effectiveness of the test.

1. Introduction
Converter transformer is one of the key equipment in converter station of HVDC transmission project. With the continuous development of UHVDC transmission project, the capacity of converter transformer has increased from 321MVA in Xiangjiaba Shanghai transmission project to 510MVA in 10GW DC project. The rated DC voltage is 800kV. The sending end is connected to 750kV AC system, and the receiving end is connected to 1000kV and 500kV AC system. After the capacity is increased, the operation of converter transformer is more complex and the conditions are more severe. However, the size and weight restrictions of the transport vehicle required for its transportation from the factory to the site have not changed, which makes the converter transformer design more compact, less margin, higher process requirements and greater quality risk. During the factory test of converter transformer, IPVD test with partial discharge specified by IEC is usually used to judge whether the internal insulation structure of converter transformer is in good condition. When a certain voltage is applied, if there are small defects in the transformer insulation, the parts with insulation defects will be repeatedly charged and discharged due to the dielectric inhomogeneity, which is commonly known as partial discharge. If the partial discharge is less than a certain threshold, the insulation is in good condition. UHV converter transformer has small design margin and high operating electric field strength. In order to ensure its insulation reliability, it is usually stipulated in the technical agreement that there is no partial discharge signal except background interference in the factory test.
In the actual production process, the inner part of UHV converter transformer is composed of tens of thousands of insulating materials, and there are thousands of winding manufacturing processes, 90% of which are manual processes. In the manufacturing process, partial discharge may occur in the IVPD test process due to local defects in materials and inadequate manufacturing process. Once partial discharge occurs, it is necessary to reduce the voltage quickly, locate the defects and repair the defects in time. The existing PD location methods include ultrasonic location and UHF location, which can assist the fault location to a certain extent. However, ultrasound and other methods can only locate the general area of discharge, such as which winding, upper or lower part of discharge occurs [1][2]. A large number of engineering tests show that there are some position deviation and interference factors. The winding structure is complex. If partial discharge is detected during the withstand voltage test, it is impossible to locate the position of partial discharge quickly and accurately. In this study, by comparing the partial discharge signal transmission relationship, the internal discharge of the winding is located. Through the distributed parameter modelling of the capacitance and inductance inside and between the windings, the typical discharge signals are applied to different positions, and the typical discharge waveforms of the tested terminals are extracted to analyse their transmission characteristics. The partial discharge waveform and transfer law of UHV converter transformer are compared with those of actual converter transformer to assist the partial discharge location in IVPD test of converter transformer [3]-[5].

2. Distributed parameter model of converter transformer winding

In the design of converter transformer, the chain network of distributed parameters is usually used to replace the actual distributed parameters to construct the equivalent circuit of the winding under impulse voltage. Because the impulse voltage is a high-frequency steep wave signal, and the electromagnetic coupling inside the coil equipment such as transformer is close, the influence of high-frequency signal is mainly reflected in the transmission process of electromagnetic transient signal. Therefore, for high-frequency signal, the use of distributed parameter circuit can effectively verify its wave process transmission procedures. PD signal is also a kind of high frequency signal, which has similar transmission model in theory, so similar methods can be used to analyse the transmission law of PD signal. In the calculation of distributed parameters, we should pay attention to the capacitance and inductance [6][7].

2.1. Equivalent capacitance parameters

The typical winding structure of converter transformer adopts double main column structure, and the outer windings of each core are arranged from inside to outside as follows: voltage regulating winding at grid side, winding at grid side and winding at valve side, as shown in Figure 1. The capacitance parameters in the equivalent circuit network of UHV converter transformer winding include: the capacitance of winding to core and oil tank (i.e. the capacitance to ground), the capacitance between windings and the longitudinal capacitance of winding. The coaxial cylinder capacitance formula can be used to calculate the ground capacitance and the capacitance between windings, and the plate capacitance formula can be used to calculate the longitudinal capacitance. The equivalent capacitance in the circuit network is derived according to the principle of equal energy, as shown in Figure 1. In this model, the main capacitance between the windings is divided according to the actual measured capacitance value, and the longitudinal capacitance of the winding is calculated according to the design theoretical value.

2.2. Equivalent inductance parameters

There are two general methods to calculate the equivalent inductance parameters of transformer windings. One is to take the yoke as an iron plane with infinite permeability. The core is bounded and its permeability is constant. The other is the model of infinite length without yoke and core, whose permeability is constant. The accuracy of the two methods can meet the calculation needs, but the second model is easier to ensure the positive definiteness of the inductance parameter matrix than the
first model, which can simplify the solution of the differential equation of the later transformer network and reduce the waste of calculation space and resources. Therefore, the latter method is used to calculate the equivalent inductance parameters of transformer windings.

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2.4. Equivalent capacitance and inductance model of winding
The equivalent capacitance and inductance models of converter transformer windings are shown in Figure 2. It includes the double cake capacitance unit of voltage regulating coil, net coil and valve coil, winding resistance, winding self-inductance and winding to ground capacitance parameters. Considering that the actual partial discharge is a high frequency signal, and the capacitance plays a major role in the actual potential distribution, the lightning impulse transfer ratio of this model is verified with the transient over voltage calculation software of the transformer plant, and the accuracy meets the actual engineering requirements.

3. Simulation calculation of partial discharge in converter transformer winding

3.1. Partial discharge model
The partial discharge signal of converter transformer winding is essentially a narrow pulse signal, which contains a large number of high-frequency components, distributed in the frequency band of 1kHz-100MHz. The rising edge of PD signal is very steep. Generally, the rising edge is only tens to hundreds of nanoseconds, while the falling edge is relatively gentle, about hundreds to thousands of nanoseconds.

For the pulse signal, scholars at home and abroad have done a lot of research work, and its mathematical models are divided into the following four categories: single exponential decay model, double exponential decay model, single exponential decay oscillation model and double exponential decay oscillation model. In this paper, the double exponential attenuation model is selected as the PD signal. The specific voltage function is as follows:

$$u(t) = U_0\left[(-e^{\frac{t}{\tau_1}}) + (-e^{\frac{t}{\tau_2}})\right]$$

$\tau_1, \tau_2$, is the time constant, $U$ is the instantaneous value of partial discharge pulse voltage. $T$ is the time in seconds, $U_0$ is the amplitude constant of PD pulse voltage. The following four wiring modes are considered in the calculation:

- **Connection mode 1**: Port 1.1 is connected to square wave signal, port 1.2 is grounded, port 2.1 is suspended, and port 2.2 is suspended.
- **Connection mode 2**: Port 1.1 is grounded, port 1.2 is connected with square wave signal, port 2.1 is suspended, and port 2.2 is suspended.
- **Connection mode 3**: Port 1.1 is grounded, port 1.2 is grounded, port 2.1 is connected with square wave signal, and port 2.2 is suspended.
- **Connection mode 4**: Port 1.1 is grounded, port 1.2 is grounded, port 2.1 is suspended, and port 2.2 is connected with square wave signal.

![Figure 3. Port diagram of converter transformer](image)

3.2. Simulation of partial discharge in windings
In the process of simulation, the partial discharge signals are input to each node of the grid side winding and the valve side winding of the transformer, and the head and end of the grid side winding
and the valve side winding of the transformer are grounded respectively to record the current amplitude of each port flowing into the earth. The parameters of partial discharge function in simulation are as follows:

\[ \tau_1 = 2.5 \times 10^{-9} \text{s}, \quad \tau_2 = 2.5 \times 10^{-7} \text{s}, \quad U_0 = 5V \]

The maximum equivalent frequency of the pulse signal is about 100MHz. The partial discharge signal is applied to each node of grid side winding and valve side winding, and the current amplitude of each port of transformer is shown in Table 1.

| Signal position (double cake position) | Current amplitude transfer ratio | Partial discharge signal is applied to grid side winding | Partial discharge signal is applied to valve side winding |
|-----------------------------------------|---------------------------------|--------------------------------------------------------|---------------------------------------------------------|
|                                        | port 2.1 | port 2.2 | port 1.1 | port 1.2 | port 2.1 | port 2.2 | port 1.1 | port 1.2 |
| 1                                      | 7.90     | 0.08     | 12.67    | 101.27   | 40.59    | 283.54   |
| 2                                      | 6.96     | 0.16     | 11.28    | 50.21    | 22.69    | 140.45   |
| 3                                      | 6.13     | 0.25     | 9.76     | 31.53    | 16.14    | 88.13    |
| 4                                      | 5.34     | 0.34     | 8.43     | 21.97    | 12.77    | 62.11    |
| 5                                      | 4.60     | 0.45     | 7.16     | 16.15    | 10.72    | 45.79    |
| 6                                      | 3.94     | 0.55     | 6.07     | 12.31    | 9.35     | 35.40    |
| 7                                      | 3.37     | 0.66     | 5.10     | 9.58     | 8.41     | 27.70    |
| 8                                      | 2.84     | 0.77     | 4.24     | 6.17     | 7.05     | 18.37    |
| 9                                      | 2.39     | 0.88     | 3.47     | 4.27     | 6.16     | 13.01    |
| 10                                     | 2.02     | 0.99     | 2.85     | 3.08     | 5.51     | 9.62     |
| 11                                     | 1.69     | 1.09     | 2.30     | 2.28     | 5.03     | 7.38     |
| 12                                     | 1.42     | 1.18     | 1.85     | 1.72     | 4.66     | 5.77     |
| 13                                     | 1.19     | 1.28     | 1.49     | 1.31     | 4.37     | 4.58     |
| 14                                     | 1.00     | 1.36     | 1.18     | 1.00     | 4.15     | 3.67     |
| 15                                     | 0.84     | 1.44     | 0.93     | 0.76     | 3.97     | 2.97     |
| 16                                     | 0.71     | 1.51     | 0.73     | 0.58     | 3.80     | 2.41     |
| 17                                     | 0.59     | 1.58     | 0.56     | 0.44     | 3.66     | 1.96     |
| 18                                     | 0.50     | 1.63     | 0.43     | 0.33     | 3.58     | 1.60     |
| 19                                     | 0.42     | 1.68     | 0.32     | 0.24     | 3.47     | 1.29     |
| 20                                     | 0.35     | 1.72     | 0.24     | 0.16     | 3.39     | 1.03     |
| 21                                     | 0.30     | 1.76     | 0.18     | 0.10     | 3.33     | 0.79     |
| 22                                     | 0.25     | 1.79     | 0.13     | 0.08     | 3.29     | 0.69     |
| 23                                     | 0.22     | 1.80     | 0.09     | 0.06     | 3.26     | 0.60     |
| 24                                     | 0.19     | 1.82     | 0.06     | 0.05     | 3.23     | 0.53     |
| 25                                     | 0.16     | 1.84     | 0.04     | 0.03     | 3.21     | 0.47     |
| 26                                     | 0.14     | 1.86     | 0.02     | 0.02     | 3.18     | 0.42     |
| 27                                     | 0.13     | 1.89     | 0.01     | 0.01     | 3.16     | 0.37     |

It can be seen from table 1 that the current amplitude of port 1.1 decreases and the current amplitude of port 1.2 increases when the amplifier signal is applied to the grid side winding and changes from the head end to the end of the winding. The current of port 2.1 increases first and then decreases, and the current of port 2.2 also increases first and then decreases.
It can be seen from table 2 that when the amplifier signal is applied to the valve side winding, the current amplitude of port 1.1 decreases and the current amplitude of port 1.2 increases when the amplifier signal changes from the head end to the end of the winding. The current of port 2.1 decreases and that of port 2.2 increases.

At the same time, considering that the frequency of PD signal may have a certain effect on the current amplitude of each port, the influence of signal frequency on the current amplitude distribution of each port is studied. In the simulation, the frequency of PD signal is changed from 100kHz to 100MHz, and the signal is applied to position 9 of grid side and valve side winding. At this time, the current amplitude of each port is shown in Table 2.

| Frequency/ Hz | Current amplitude / A |
|---------------|-----------------------|
|               | Applied to the grid side winding | Applied to the valve side winding |
|               | port 2.1 | port 2.2 | port 1.1 | port 1.2 | port 2.1 | port 2.2 | port 1.1 | port 1.2 |
| 100k          | 0.0058   | 0.0015   | 0.0051   | 0.0021   | 0.0058   | 0.0015   | 0.0051   | 0.0021   |
| 1M            | 0.058    | 0.015    | 0.051    | 0.021    | 0.058    | 0.015    | 0.051    | 0.021    |
| 10M           | 0.58     | 0.15     | 0.51     | 0.21     | 0.58     | 0.15     | 0.51     | 0.21     |
| 100M          | 5.76     | 1.46     | 5.07     | 2.12     | 5.76     | 1.46     | 5.07     | 2.12     |

It can be seen from table 3 and table 4 that changing the frequency of PD signal only affects the amplitude of port current. The frequency of PD signal is increased by 10 times, and the amplitude of port current is also increased by 10 times. However, changing the frequency of PD signal has little effect on the current distribution of each port, and the current distribution is basically consistent.

3.3. Simulation of partial discharge outside winding

The simulation of partial discharge outside the winding is shown in Figure 4. By increasing the capacitance to the ground, the partial discharge outside the winding (such as in the main insulation) is simulated. In this case, the calculation results show that the external partial discharge has little influence on the calculation results of winding transfer ratio.

![Figure 4. Schematic diagram of partial discharge outside simulated winding](image-url)
4. Partial discharge test case of a converter transformer

During the partial discharge test of a converter transformer, the discharge characteristics are as follows:

- (1) 00 min and 00 s to 941 kV
- (2) The partial discharge signal appeared in valve 2.1 from 19min22s to 43min00s, lasting for about 24 minutes. And the typical partial discharge transfer at this time is shown in table 3.

| Position | Port 2.1 | Port 2.2 | Port 1.1 | Port 1.2 | Core | Clamp |
|----------|----------|----------|----------|----------|------|-------|
| Corrected transfer ratio | 1 | 7.4 | 4.8 | 10.9 | 6.5 | 5.8 |

The transfer ratio of 2.1 to 2.2 on the valve side of the clamp varies from 101.27 to 0.01. When the discharge position is close to the end 2.1, the transfer ratio is larger, and decreases with the decrease of the discharge position along the height of the valve side winding. Based on this method, it is qualitatively determined that the partial discharge occurs in the middle and upper region of the valve 2.1 end winding.

5. Conclusion and Prospect

In this research, a simulation model of ±800 kV converter transformer based on distribution parameters is built. The partial discharge signals applied at different positions in the winding are simulated and compared with the test results.

(1) The second model built in this work has been verified with Siemens transient overvoltage calculation software for lightning impulse transfer ratio, and the accuracy meets the requirements of engineering practice, which can be used for auxiliary judgment of internal discharge location of winding in partial discharge test.

(2) For the external voltage withstand test case in this report: assume that the discharge occurs near the valve side winding, and the discharge signal transfer ratio changes with the different positions of the discharge signal coil height. The transfer ratio of 2.1 to 2.2 on the valve side ranges from 101.27 to 0.01, and the transfer ratio of 2.1 near the end is larger, and the transfer ratio decreases with the decrease of the discharge position along the height of the valve side winding. The model can be used in the factory test of converter transformer to determine the discharge position.

This model has good applicability for the analysis of high frequency discharge signal transmission characteristics in the range of 100k-100mhz, but it cannot fully consider the mutual inductance coupling between the windings. Through the corresponding algorithm and program development, the mutual inductance coupling situation can be further improved, the calculation accuracy can be improved, and the discharge position can be further analyzed accurately. In practice, the model is applicable to the partial discharge in the winding. However, for the partial discharge outside the winding (such as end insulation, core insulation and other parts), due to the structural characteristics, it is impossible to calculate the partial discharge through the coupling of distributed parameters. It is still necessary to combine with UHF, ultrasonic and other partial discharge monitoring means, and carry out box entry, hanging cover or disassembly inspection when necessary to check the defects of converter transformer.

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