Study on transient voltage distribution characteristics of transformer windings

ABSTRACT

Very fast transient overvoltage (VFTO) with large waveform steepness and high amplitude can cause great harm to winding insulation of transformers and other equipment connected to it. Therefore, a transformer winding model is designed and described in this paper. Transient overvoltage test is carried out by pinning method and non-contact measuring sensor respectively. Then the simulation results are compared with those of VFTO distribution calculation program for transformer equipment. The results show that the simulation results are close to the actual test results. Finally, combining with the experimental measurement and simulation data, the potential distribution in transformer windings under the effect of fast transient overvoltage is analysed to guide the overvoltage protection of transformer winding insulation.

KEYWORDS

very fast transient overvoltage, transformer winding, non-contact measuring sensor, measurements, simulation, voltage distribution

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Very fast transient overvoltage with high amplitude and high waveform steepness can cause great harm to winding insulation of transformers and other equipment connected to it

1. Introduction

Presently, GIS is widely used in EHV/UHV transmission networks. When disconnector is switched on or off in GIS, the moving speed of disconnector's moving contacts is relatively slow, which leads to multiple breakdown of SF6 gas gap between disconnectors. Each breakdown will cause the voltage of disconnector to drop within several nanoseconds, and produce very steep voltage traveling wave, which propagates on both sides from the disconnector and causes high frequency oscillation on GIS and adjacent devices. This is the formation of Very Fast Transient Overvoltage phenomena. The waveform of VFTO is steep and its amplitude is high, which could do great harm to the winding insulation of transformer and other equipment connected with it [1].

Since the discovery of the VFTO phenomenon in GIS, whether large power transformers can withstand the impact of VFTO and how to eliminate the impact of VFTO, have been the concerns of power system.

Presently, in the design and manufacture of UHV transformer, the analysis of VFTO is mainly based on the theoretical analysis conclusions in the references and calculation with simplified transformer model. Therefore, the method of increasing margin is adopted in structural design and insulation measures, lacking the necessary data support for field measurement and research.

Due to the limitation of computing speed and storage capacity of the computer, the previous calculation is limited by the number of units for winding partitioning or can only analyse windings with fewer turns, and the inductance and capacitance parameters in the model are centralized and constant, without considering the frequency-varying parameters of the conductor due to skin effect. The model is relatively simple, and the calculation accuracy is poor.

In this paper, multi-conductor transmission line (MTL) model based on the representation of the winding by its individual turns is used to analyse the transient response of transformer windings under Very Fast Transient Overvoltages (VFTO). The unequal-length multiconductor transmission-line (MTL) model is adopted in considering the actual configuration of the transformer circular winding and the finite element method in time domain is used to calculate the voltage distributions along transformer windings by means of vector fitting and recursive convolution to dispose the frequency-dependent parameters [2].

The pinning method is used to measure the voltage distribution of transformer windings. The pinning method is the destructive test of insulation. By embedding metal probes inside the windings, the voltage of discs on the winding can

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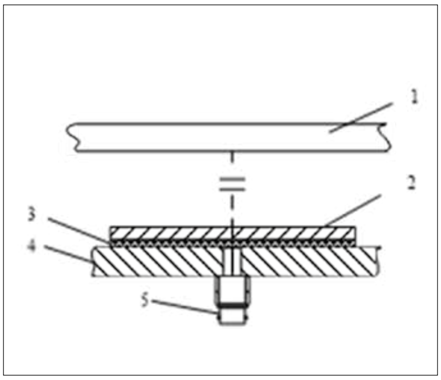


1-transformer disc; 2-copper electrode; 3-polyester film; 4-outside metal shell; 5-BNC connector plugs

Figure 1. Schematic diagram of capacitance sensor

be measured directly by using high voltage probes and other devices [3]. The method is simple, and the results are accurate, but it will damage the insulation of the windings. If the probes used are too large, they will cause damage to the insulation of the windings. The distribution parameters of windings are often changed, so that the measured results are not in conformity with the engineering practice.

Although theoretical simulation and measurement methods have been studied, these studies are isolated and limited. Therefore, it is of great significance to study the transmission distribution of transformer windings under VFTO to optimize the design of transformer insulation structures.

In order to study the distribution characteristics of transformer winding transient overvoltage, this paper takes the actual transformer winding model as the test object, and uses the transformer winding transient voltage testing platform based on coupling capacitance sensor and compares it, respectively, to the pinning method and non-contact sensor method. The comparison between simulation and actual winding measurements is also discussed to verify them and to study the distribution of transient voltage in windings.

2. Non-contact measuring sensor

The basic principle of non-contact measuring sensor is to use the coupling capacitance between transformer winding conductor and sensor electrode as the high-voltage arm capacitance of capacitance divider, and the insulating medium capacitance between sensor electrode and metal shell as the low-voltage arm capacitance. The principle of capacitance divider is used to measure the high voltage on transformer winding [4], [5]. The structure of a coupling capacitance sensor used in the experiment is shown in Figure 1 and Figure 2.

(a) Front of the sensor

(b) Back of the sensor

Figure 2. Picture of the sensor

The coupling capacitance between the copper electrode and the winding conductor is the high voltage arm capacitance of the voltage divider, and the polyester film between the copper electrode and the aluminium shell is the low voltage arm capacitance of the voltage divider.

The VFTO response characteristics of the sensor are verified by the experimental circuit shown in Figure 3. The VFTO generated by the impulse voltage generator has front rise time of about 50 ns and the superimposed high oscillation frequency is about 10 MHz, which meets the requirements of IEC 60071-1 standards [6] for steep front waveforms, as shown in Figure 4.

3. Test winding model

The transformer winding is the circuit part of the transformer. According to the principle of impulse wave transmission and distribution in windings, the potential gradient at the winding end is $\alpha\iota$ times larger than the gradient 1 of the pseudo final voltage distribution. The smaller the $\alpha\iota$ is, the smaller the maximum gradient is, the more uniform the gradient distribution is, and the better the impact performance of the winding is. $\alpha\iota$ is determined by the following equation (1):

$$\alpha\iota = \iota\left(\sqrt{\frac{C}{K}}\right) = \left(\sqrt{\frac{C_0}{K_0}}\right) \quad (1)$$

Where:
C is the capacitance per unit length to ground of the winding,
K is the longitudinal capacitance per unit length to ground of the winding,
ι is the total winding length,
C_0 is the total ground capacitance of the winding,
K_0 is the total longitudinal capacitance of the winding.

From the point of view of improving impact distribution, continuous capacitor shield, interleaved winding or combinations of several structures are usually used.

In order to meet the research needs, a model of sandwich interleaved-interleaved-continuous combination winding is designed. The parameters of the model are shown in Table 1.

The wire used in this wingding is paper insulated composite wire which is a combination of two single wires; turns insulation is 1.35 mm.

The oil channel is arranged as follows: 6 and 8 interlaced in the sandwich-interleaved interleaved type winding, 4 and 6 are interlaced in the continuous type winding parts.

The connection diagram of test winding model is shown in Figure 5. The winding is a longitudinal symmetry; only the first half (1-54, 55) is indicated in this paper.

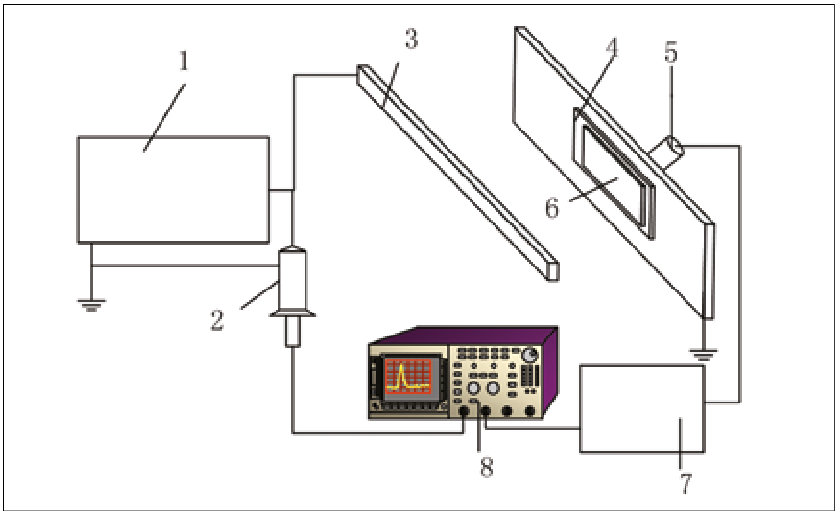
4. Model test of winding

In order to study the impact of VFTO on transformer windings, it is necessary to apply a pulse voltage which can simulate VFTO on the windings. At present, two kinds of waveforms are usually used to simulate:

1. Double exponential impulse voltage with steeper wave front to simulate the situation when VFTO has steep rising edge;
2. Unipolar impulse voltage with oscillation frequency in MHz to simulate the characteristics of VFTO with oscillation component.

In order to verify that the non-contact voltage sensor can be used for practical measurement, while considering the necessity of studying the standard lightning impulse that the transformer winding must withstand, the voltage distribution of the winding model under three typical impulse voltage waveforms (standard lightning wave, steep front double exponential wave and high frequency oscillation wave) is measured by the sensor. Compared with the potential signal measured by pinning method, the non-contact sensor can be used to measure the potential distribution of windings.

Presently, in the design and manufacture of UHV transformer, the analysis of VFTO is mainly based on the theoretical conclusions and calculations with simplified transformer model



1-impulse generator; 2-high-voltage probe; 3-copper bar; 4-polyester film; 5-BNC connector plugs; 6-sensing copper; 7-signal processing; 8-oscilloscope

Figure 3. Schematic diagram of an experimental circuit

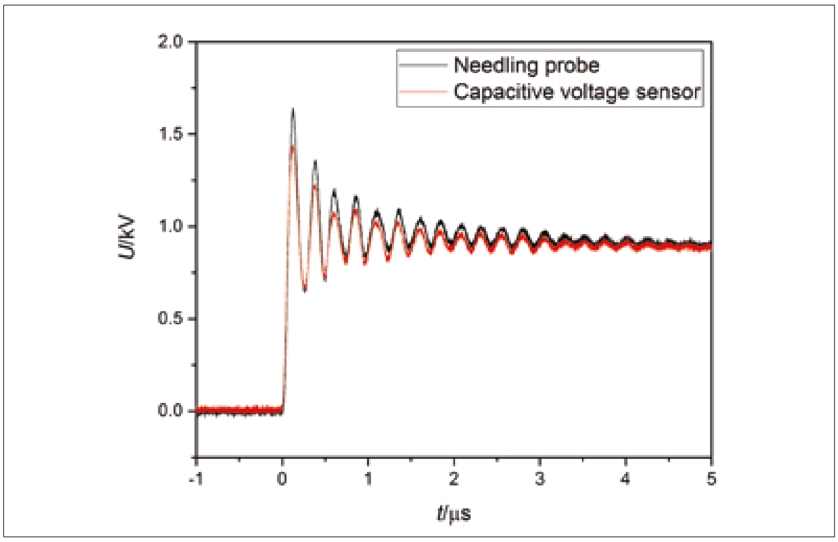


Figure 4. The output of the measurement system under VFTO

Table 1. Basic parameters of test winding model

Name of the disc	Number of disc	Total turns	Number of parallel wires	Wires (Paper insulated composite wire)	Internal diameter/mm
L1	8	104	2	$ZZ - 1.35 \dfrac{2 \cdot 2.12 \cdot 10}{5.59 \cdot 11.4}$	906
L2	16	224	2		900
G	8	112	2	$ZZ - 1.35 \dfrac{2 \cdot 2.24 \cdot 10}{6.23 \cdot 11.4}$	898
G1	76	1064	2		898

L1: sandwich-interleaved type winding; L2: interleaved type winding; G, G1: continuous type winding;

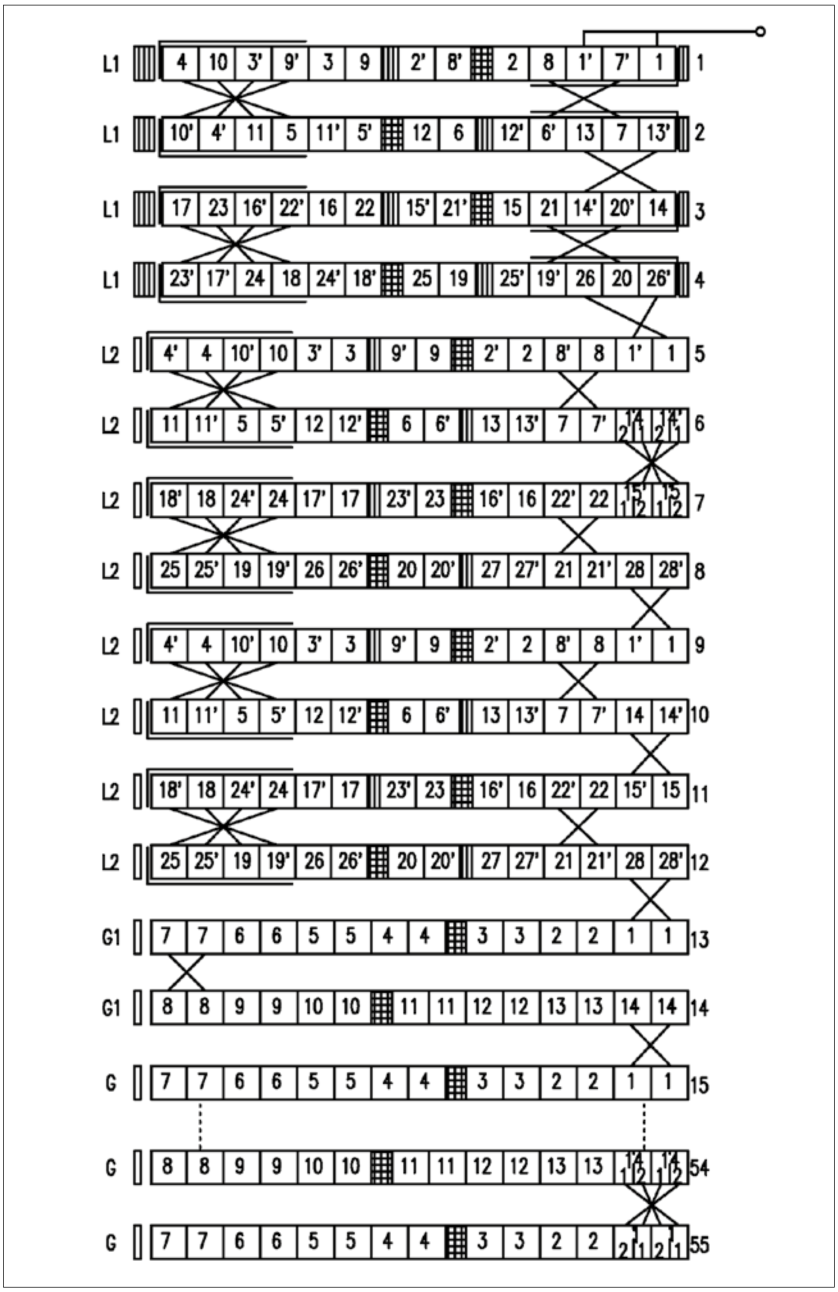


Figure 5. Connection diagram of a test winding model (upper part of the winding)

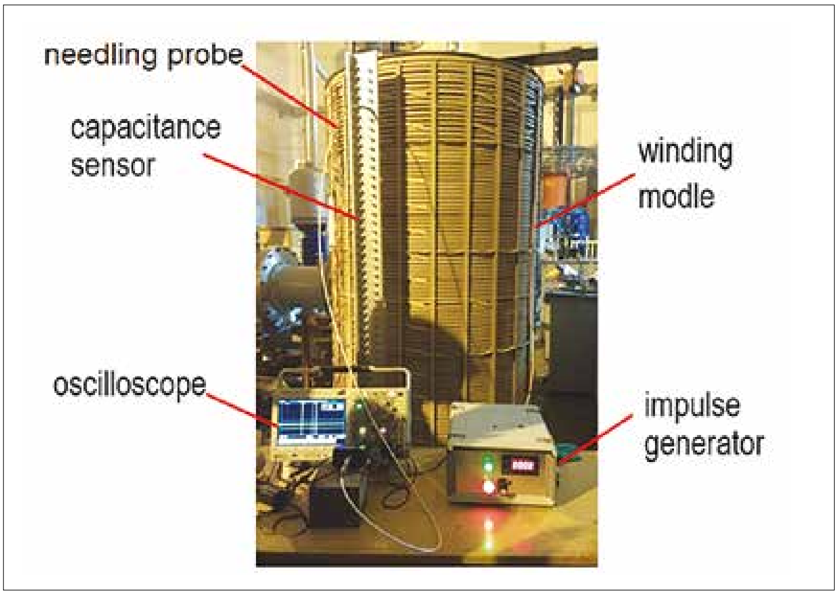


Figure 6. The test platform

In this study a test platform is used to research the impulse transmission along the entangled winding model by non-contact measuring sensor and needle probe

The test platform is shown in Figure 6. The test voltage of up to about 3 kV can be generated through this platform. The sensor is about 10 cm away from the winding. Metal needling probes are arranged on every two discs on the winding. There are 108 discs in the winding and a total of 1504 turns. In order to simulate the effect of iron core, a coaxial aluminium shielding barrel is placed inside the winding and a grounding bolt is installed at the end of it to ground it. Since transformer oil does not have a great influence on voltage transmission, and in order to facilitate the comparison of the two test methods, the oil-immersed state of winding with tank is not considered in this test.

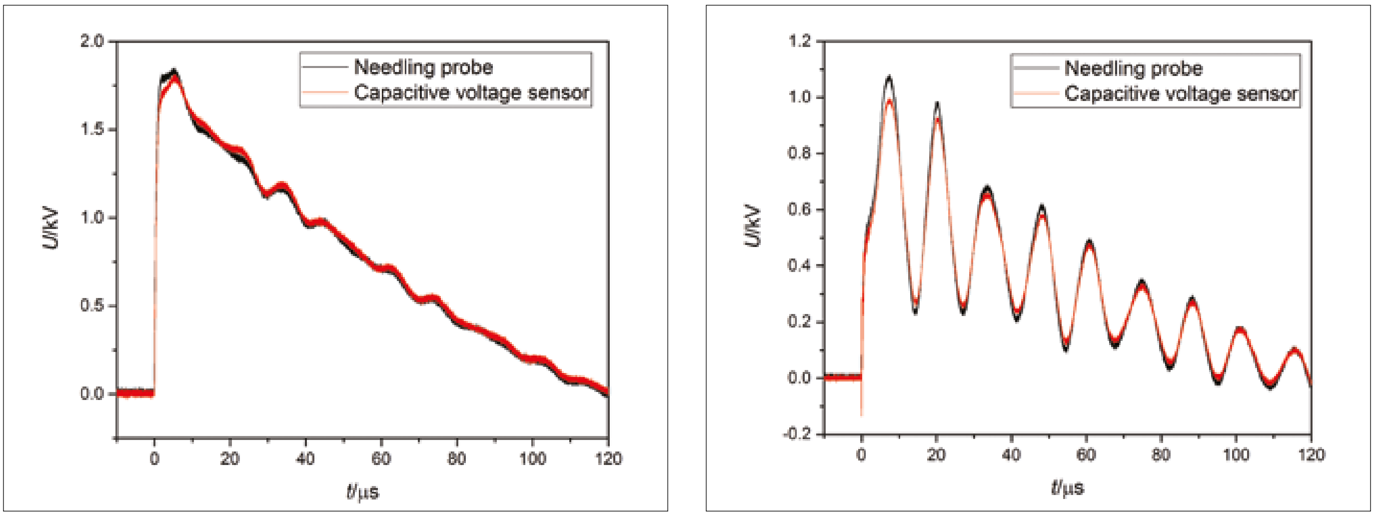
Figure 7 shows the output signals of the 4th and 62nd disc sensors at the end of disc and needling probe on corresponding discs which is embedded in the winding when standard lightning wave (1,2 / 50 μs) is applied from the top and the end of the winding is grounded.

Figure 8 shows the output signals of some sensors and needling probes on corresponding discs when applying steep front double exponential waves (0.1 / 50 μs).

Figure 9 shows the output signals of some sensors and needling probe on corresponding discs when applying high frequency oscillation wave (100 ns rising edge 3.5 MHz attenuation oscillation).

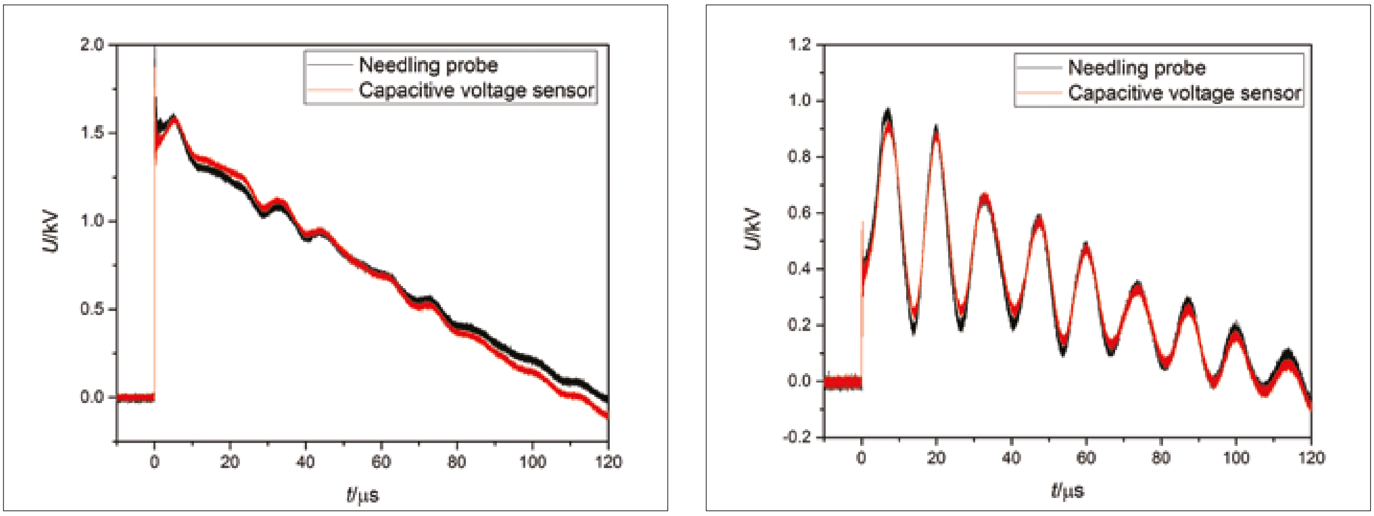
It can be seen that the sensor has good response characteristics when measuring the winding potential distribution under the previously mentioned three typical impulse voltages. The slight difference between the two measurements is mainly due to the fact that the needle

Non-contact measuring sensor can be used instead of needle probe in order to study the transient voltage distribution



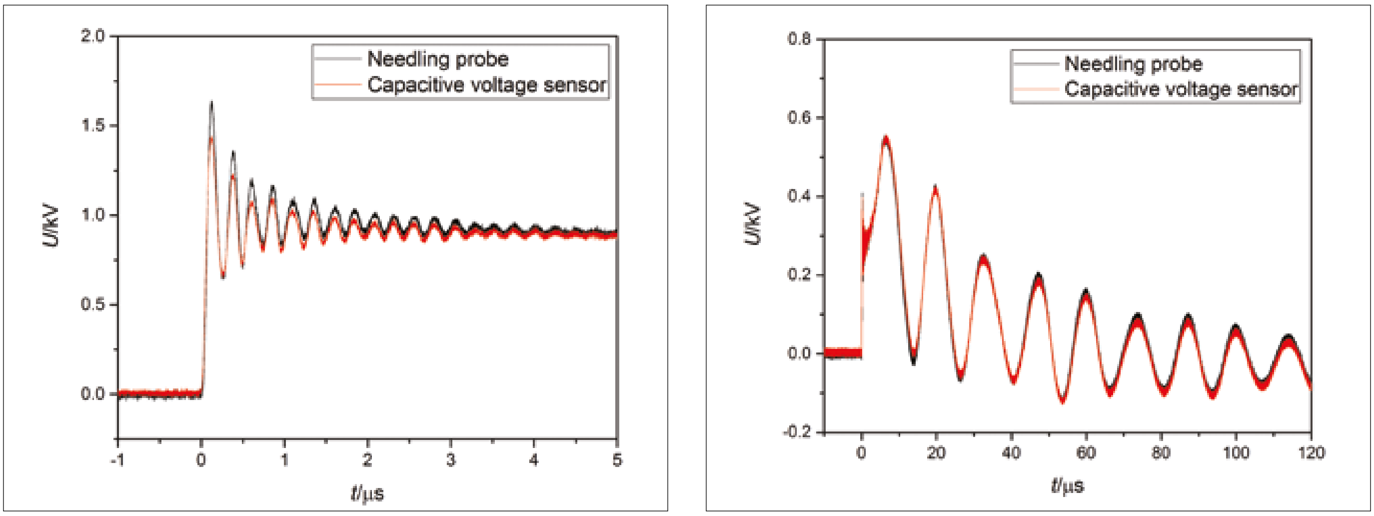
(a) the 4th disc (b) the 62nd disc

Figure 7. Comparison of measurement signals under standard lightning wave



(a) the 4th disc (b) the 62nd disc

Figure 8. Comparison of measurement signals unde r double exponential wave with steep front



(a) the 4th disc (b) the 62nd disc

Figure 9. Comparison of measurement signals under high frequency oscillation wave

Since transformer oil does not have a great influence on voltage transmission, and in order to facilitate the comparison of the two test methods, the oil-immersed state of winding with tank is not considered in this test

probe can damage the insulation of the windings, and the direct electrical connection may change the distribution parameters of the transformer windings, leading to changes in the transient process, making the measured results inconsistent with the actual situation.

Because lightning impulse wave is a routine test item of insulation test, and VFTO wave has the characteristics of steep wave front and high frequency, it is difficult to realize the common test instrument. The previously mentioned three test waveforms have the typical characteristics of insulation test and VFTO, so the coupling capacitance sensor can be applied to the measurement of winding potential distribution.

5. Comparison of simulation and measurement

In practical engineering application, we developed a program based on the transformer winding model of unequal length, multi-conductor transmission line, and applied time-domain finite element method to simulate the voltage distribution of transformer winding under VFTO. In order to verify the correctness of the methods used in the simulation calculation, the transient voltage distribution of the above transformer winding model is simulated by a program and verified by the test platform. If the simulation results are close to the actual test results, the simulation method can guide transformer winding over-voltage insulation protection.

A high voltage pulse source with an am-

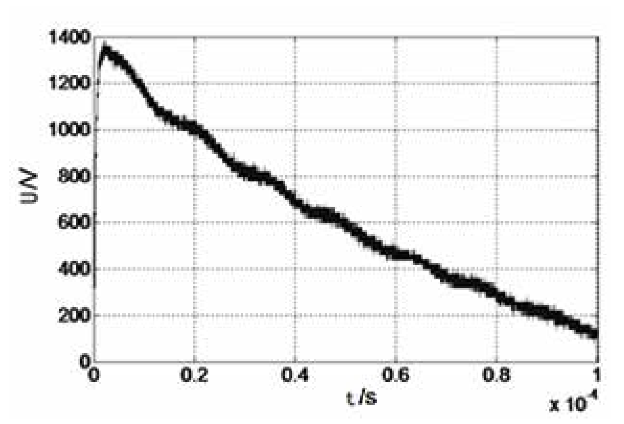


Figure 10. Input transient excitation signal

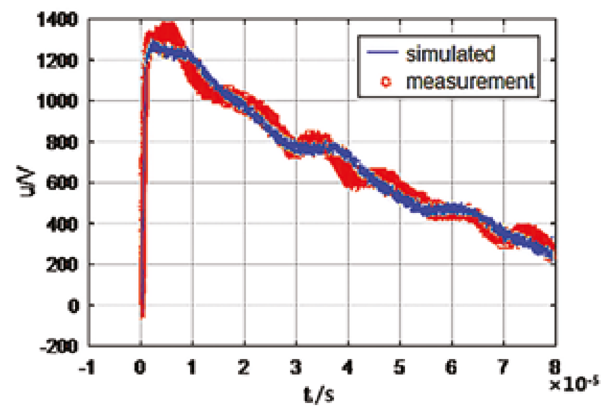


Figure 11. Comparison of measurement and simulated results of the 5th disc end

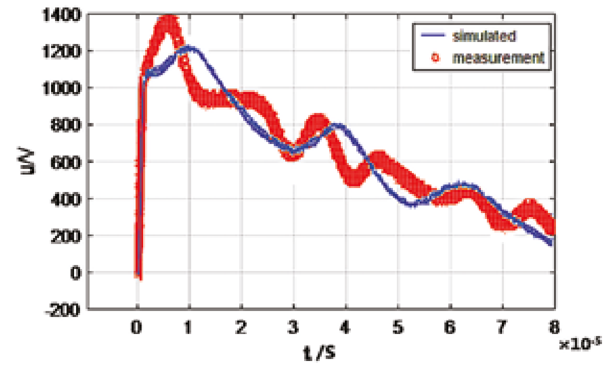


Figure 12. Comparison of measurement and simulated results of the 10th disc end

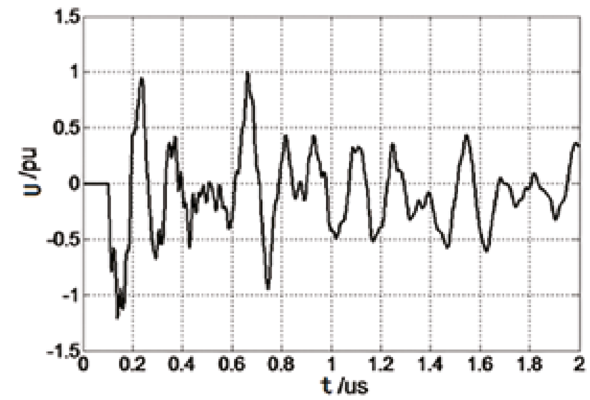


Figure 13. Input voltage waveform of the 1st disc

plitude of up to about 100 ns / 50 µs is used as the impulse signal source, and its output signal is the transient waveform shown in Figure 10. Figure 11 is a comparison of measurement and simulated results with our program of the 5th disc end. Figure 12 is a comparison of measurement and simulated 10th disc end.

Different winding structures lead to different longitudinal capacitance, which leads to the change of potential distribution, and this can be used to optimize the transient voltage distribution characteristics of windings

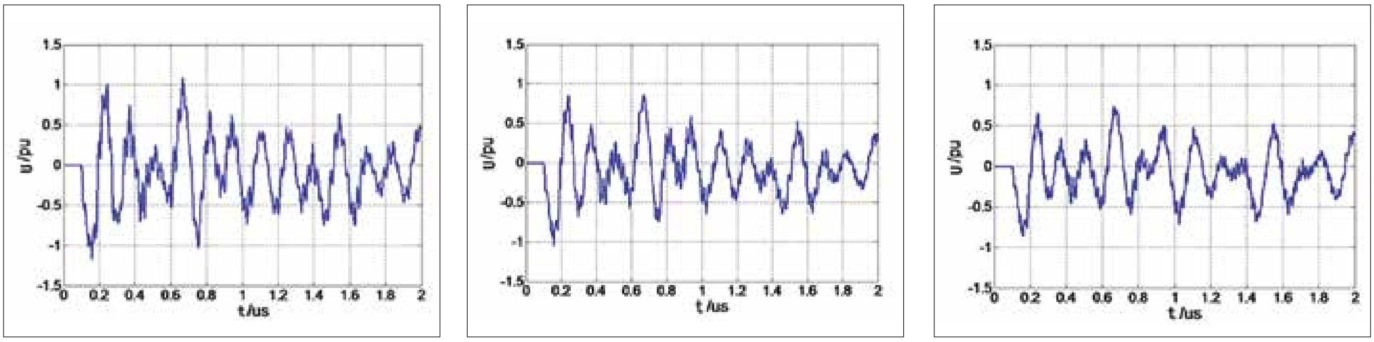
By comparing the transient overvoltage impulse experiment with the numerical simulation results, it can be seen that when the transformer winding is impacted by the transient wave, the measured results are approximately the same as the numerical simulation results.

6. Distributed simulation of transformer winding VFTO

The correctness of the program simulation is verified by the experiment and simulation calculation of the previously mentioned windings. Input voltage waveform of the 1st disc is shown in Figure 13, the output waveform of each disc end of the winding is shown in Figure 14, the maximum potential of each turn is shown in Figure 15, the maximum voltage between turns and the potential gradient between discs are shown in Figure 16 and Figure 17, respectively.

The simulation results show that under the influence of the VFTO signal, the maximum inter-turn voltage difference of the transformer winding model appears between conductors number 1 and 8, which is about 0.16 p.u. The peak value of voltage, except for the first line disc at the input end, is located in the second disc, which is about 1.2 p.u. input voltage, and then decays rapidly. The main reason for this phenomenon is that the transient transmission has an oscillating process.

According to the maximum voltage curve between turns in Figure 16, the maximum interturn voltage is about 16 % in 1st disc, and then begins to constantly decrease; and the 4th cake (about 52 turns), when reduced to less than 12 %, and the 12th disc (about 164 turns) quickly drops to 5 %, the disc former 16 cake (about 220 turns) voltage drops relatively quickly, then the voltage gradient distribution decreases slowly. In this paper, it is believed that the change of voltage drop rate near the 4th and 12th disc is due to the change of coil structure at the place where the coil is: 1~4 disc is sandwich interleaved winding, 5~12 disc is ordinary interleaved winding, and then turns into continuous winding. Different coil structures lead to different longitudinal capacitance of the windings, which leads to the change of potential distribution. This shows that the entangled coil structure can optimize the transient voltage distribution characteristics of the transformer windings in the rapid transient process.



(a) signal of the 2nd disc end (outside diameter side)

(b) output waveform of the 6th disc end (outside diameter side)

(c) output waveform of the 10th disc end (outside diameter side)

Figure 14. Output waveform of the disc end

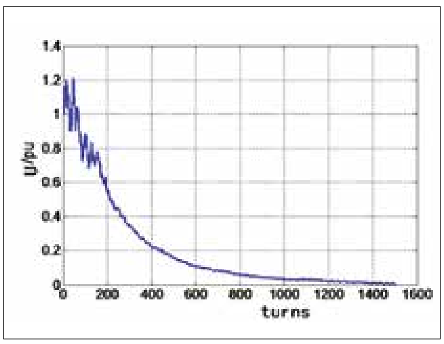


Figure 15. Maximum electric potential of turns

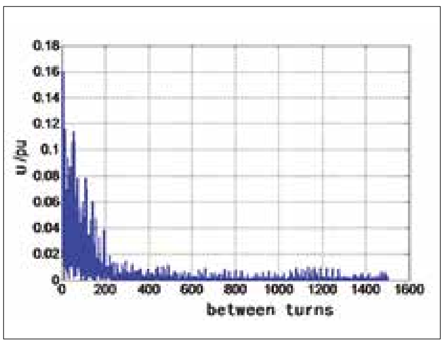


Figure 16. Maximum voltage between turns

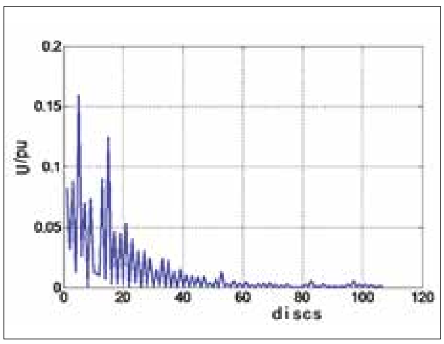


Figure 17. Potential gradient between discs

The rationality of the simulation is verified by comparing the test data with the simulation data

The simulation results show that when VFTO, and other fast transient overvoltage signals, are applied to the winding end, the maximum potential of winding discs and turns appears at the head discs, and the maximum value of potential gradient between discs and turns is also located at the head discs. If we give a quantitative description of the so-called "head discs" here, it is recommended to use the figure of 20 % according to the simulation experience. In order to achieve ideal and reliable potential distribution, a specific step capacitance compensation can be carried out in combination with specific simulation in engineering production [7].

Conclusion

In this paper, the transient voltage distribution test platform is used to test the impulse transmission along the entangled winding model by non-contact measuring sensor and needle probe respectively. The conclusion that the non-contact measuring sensor can be used to study the transient voltage distribution is drawn. At the same time, the rationality of the simulation is verified by comparing the test data with the simulation data. Suggestions for the compensation of transformer winding capacitance in engineering application are put forward. For example, high voltage coils can be compensated by staged capacitance, which can be selected according to different voltage levels. Some combination designs of sandwich interleaved-interleaved across 4 discs capacitor shield winding, 2 discs capacitor shield winding, or continuous combination winding can improve the potential distribution to enhance the ability to withstand VFTO.

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