Measurement of the voltage distributions over transformer winding in standard lightning impulse voltage

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Abstract. This paper mainly focuses on the distribution of the standard lightning impulse (LI) voltage over transformer windings. In order to obtain the voltage waveform of different windings, the test platform contains an impulse voltage generator and a 35kV transformer model with multiple winding taps is built. Results of the distribution voltage are provided. The lightning impulse voltage distributes in a nonlinear way. The distort waveforms show the internal oscillations of the winding and resonant frequencies are in the range of several hundreds of kilohertz. The voltage difference between windings is larger in some specific windings, which gives some references for interturn insulation design.

1. Introduction
To ensure the safe and stable operation of power transformers, lightning impulse (LI) has been widely used to tests the insulation of windings of transformers. Due to the electrostatic induction or electromagnetic induction, the internal resonances may be excited and the lightning impulse voltage distributes in a very nonlinear way, which can cause overvoltage in some parts of the windings. In addition, the interturn voltage distribution is of great reference to the interturn insulation of transformer windings, for the large turn-to-turn voltage may destroy the turn-to-turn insulation and cause faults. The different distribution between the initial voltage and the steady-state voltage over the transformer windings is the fundamental reason for the oscillation. Thus, by measuring the distortion of the impulse voltage between the windings of the transformer, it can be observed that the whole states from transient to steady.

Simulation and measurement of the distribution of impulse voltage over transformer windings during LI tests have been carried out for many years [1, 2]. The difference of impulse voltage distribution between intershield disk winding and continuous disk winding has been compared in [3]. Simulation models are built to calculate LI voltage distribution in power transformers [4, 5], and a novel method for accurate high-frequency modelling of dry-type transformer windings based on magnetic and electric field simulations has also been put forward [6].

However, the voltage between the windings and the LI voltage distortion have not been taken much into consideration. In this paper, the voltage distribution of transformer during a standard 1.2μs/50μs LI applied to its winding is measured. The voltage peak distribution, the voltage between windings, and the distortion of waveform are mainly analysed.
2. Test system and measurement method

2.1. Generation of lightning impulse voltage

As is shown in figure 1, lightning impulse voltage rises rapidly to a peak value and then falls without oscillations more slowly to zero according to IEC 60060-3:2006. The front time, defined as 1.67 times the interval between the instants when the impulse is 30% and 90% of the peak value, ranges from 0.8μs to 20μs. Time-to-half-value, defined as the time between the virtual origin and the instant when the voltage decreased to half the peak value, ranges from 40μs to 100μs.

The circuit diagram of the impulse voltage generator is shown in figure 2. The main capacitor Cs is charged from a direct voltage source. When the sphere gap breaks down, impulse voltage is generated on the test piece through front resistance Rs and terminal resistance Rp. Cb and L is the capacitor and inductor used to change the waveform of LI. The value of Cs, Rs, Rp, Cb and L can be changed to generate a suitable impulse voltage waveform. The front time and time-to-half-value of LI can be calculated as follow equations:

\[
T_f = 3.24 \frac{RC_b C_s}{C_s + C_b'}
\]

(1)

\[
T_t = 0.693(R + R_p)(C_s + C_b')
\]

(2)

where \(C_b'\) is \(C_b\) paralleled with the capacitance of the test piece.

According to the test data and the actual situation, the value of Rs is 470ohm, and that of the terminal resistance Rp is 68ohm. The main capacitor is 1000nF, and Cb and L equals zero. The actual waveform obtained from the test is shown in figure 3. The measured front time is 1.15μs and the time-to-half-value is 49.32μs, which complies with the requirements of the standards.

![Figure 1. The standard lightning impulse voltage.](image1)

![Figure 2. Circuit of the impulse voltage.](image2)

![Figure 3. The waveform of the lightning impulse voltage in the tests.](image3)

2.2. The transformer and measurement method

In order to study the deformation of transformer winding and the voltage distribution, a three-phase two-winding transformer is used during the tests. The transformer is ST-3150kVA/35kV/400V with core inside, and its continuous windings are exposed to the air without a tank outside. The C-phase
winding of the transformer has 53 taps (numbered 1-53) to simulate the fault of the transformer and acquire the voltage waveform at different positions. The specifications of the tested transformer are presented in table 1.

| Type of winding | Number of layers | Number of turns in a layer | Height of winding | Rated voltage | Diameter of core | Height of core |
|----------------|------------------|---------------------------|------------------|---------------|-----------------|---------------|
| LV             | Continuous       | 24                        | 1                | 420mm         | 0.4kV           | 188mm         |
| HV             | Continuous       | 175                       | 12               | 460mm         | 35kV            | 471mm         |

The test was carried out in the C phase of the transformer. Through measurements, it is found that when the low-voltage(LV) winding is applied a voltage, the highest frequency of induction voltage in high-voltage(HV) winding is up to 6kHz, which is much lower than that of lightning impulse voltage. Thus, LI voltage is applied directly to the HV winding and measured by a standard oscillograph. The sampling rate of the oscillograph is selected as 5M/s, and 200ms the time of the waveform is recorded.

3. Results of the voltage distribution over windings

Figure 4. the voltage waveform of different windings.
The obtained measurement results for different winding positions are shown in figure 4. The voltage of the first three windings is basically undistorted, but there is an obvious distortion since No.5 windings. The waveforms at different positions in figure 4 show the internal oscillations of the winding and resonant frequencies are in the range of several hundreds of kilohertz. When the applied standard LI rises to the voltage peak, the voltage of the measured winding is not maximal, but rises to its peak after an oscillation. After the distortion voltage wave reaches its peak, there will be about 8 oscillations and then decays to 0. The oscillation voltage waveform is basically the standard waveform as the envelope from No.1 winding to No.32 winding, but after No. 33 winding, the envelope is lower than the standard waveform. There are high frequency oscillations in the front wave, and the larger the number of the winding, the stronger the oscillation. As a result, negative value of voltage appears in the front wave.

The normalized peak value of the voltage at different positions is shown in figure 5, and the normalized voltage difference between windings is shown in figure 6. The peak value declines slowly in the first 32 windings and drops rapidly after the No. 33 winding, which means the first 32 windings of the transformer withstand high voltage. Besides, in some windings at 3~5 and 32~42 windings, the voltage difference between the windings is larger than others.

4. Conclusions
The lightning impulse voltage distributes in a nonlinear way that the peak value of the voltage declines slowly in the first 32 windings which means these windings withstand a higher voltage. The distort waveforms show the internal oscillations of the winding and resonant frequencies are in the range of several hundreds of kilohertz, especially in the front of the voltage waveform. The voltage difference between windings shows that it’s larger in some windings at 3~5 and 32~42, which gives some references for interturn insulation design.

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