

# Conduction and Coupling Test of Lightning Current Invading the N-line of Box-type Transformer

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**Abstract** In theory, due to the fact that the grounding wire PE of wind turbine and the N-line (directly grounded) of the Y-shaped wiring on the low-voltage side of the box-type transformer share the grounding body, when the wind turbine is struck by lightning, the lightning current is directly conducted to the N-line on the low-voltage side of the box-type transformer (invasion mode of transformer synonym end). At the same time, conducted overvoltage pulse is generated in the three-phase winding on the low-voltage side, and coupled to the high-voltage side of the box-type transformer ( $\Delta$  connection) to generate coupling overvoltage pulse. After investigation, the existing regulations on the tripping rate of power lines have not taken into account the impact of wind turbines being struck by lightning on line tripping, and the mechanism is still unclear. In order to further analyze the causes of lightning tripping of collection line circuit breakers in wind farms, it is necessary to study the physical process of how lightning current is conducted (coupled) to the collection line through the box-type transformer after lightning strikes on the wind turbines. In this paper, the test method of "conduction and coupling test of lightning current invading transformer N-line", and the waveform parameters (polarity, phase, amplitude, and transformation ratio) of the primary and secondary windings of the box-type transformer when lightning current invades the transformer N-line are introduced. It can provide assistance for operation and maintenance personnel to analyze the reasons for lightning tripping of 35 kV line circuit breakers in wind farms.

**Key words** Wind farm; Box-type transformer; Lightning current invading N line; Conduction and coupling test

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So far, frequent tripping of 35 kV overhead line circuit breakers in wind farms caused by lightning strikes is still a common phenomenon<sup>[1]</sup>. The reasons for circuit breaker tripping are generally believed to be in four forms: lightning strikes on lightning protection wires (ground wires), conductors (winding strikes), towers (counterattacks), and near the line. Measures such as installing lightning protection wires, improving tower insulation levels, and reducing tower grounding resistance are adopted for lines that frequently trip due to lightning strikes<sup>[2]</sup>.

However, wind farms have a link characteristic of generating electricity from wind turbines, boosting with box-type transformers, transmitting through overhead lines, and integrating into the power grid after further boosting at the boosting station<sup>[3]</sup>. Among them, the geographical environment determines that the wind farm is an area with high probability of lightning strikes<sup>[4]</sup>. When lightning strikes the wind turbine, the lightning current directly invades the N line at the low-voltage side of box-type transformer (Y-shaped connection) through the grounding wire of wind turbine. In order to understand its impact on the tripping

of line circuit breakers, the conduction and coupling test of lightning current invading the N-line of transformers is carried out. The test results are applicable to all transformers with Y/ $\Delta$  connection.

## 1 Test equipment and lightning current waveform parameters

**1.1 Test equipment** GIC-150 impulse current generator, GIC-150 impulse current generator console; three-column three-phase dry-type transformer (380/690 V) (380 V/ $\Delta$  connection at low voltage side, 690 V/Y connection at high voltage side); two dual channel Tektronix oscilloscopes, current sensor, small inductance capacitance tester, etc. Inductance and capacitance parameters of transformer are shown as Table 1.

**Table 1 Inductance and capacitance parameters of transformer**

Transformer measurement location	Interstage capacitance $C//\mu\text{F}$	Y winding inductance mH	$\Delta$ winding inductance mH
A phase	499.30	166.32	48.76
B phase	452.44	172.75	49.16
C phase	474.78	170.65	50.32

**1.2 Parameters of lightning current impulse waveform** Three-phase dry-type transformer 380/690 (Y/ $\Delta$ ) is used to simulate a box-type transformer<sup>[5]</sup>. Positive-polarity pulse currents  $T_1 = 8.10 \mu\text{s}$ ,  $T_2 = 22.53 \mu\text{s}$ ,  $I_p = -4.81 \text{ kA}$ , ( $-0.668 \text{ kA}$ ) and negative-

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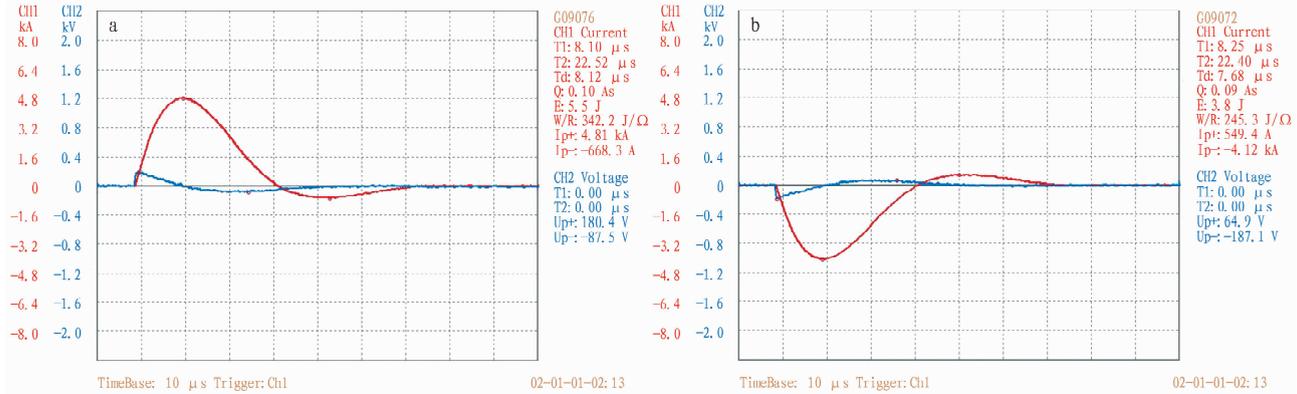
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polarity pulse currents  $T1 = 8.25 \mu\text{s}$ ,  $T2 = 22.4 \mu\text{s}$ ,  $I_p = -4.12 \text{ kA}$ , ( $+0.54 \text{ kA}$ ) are applied to the N-line of the Y connection on the high voltage side (690 V). The parameters of lightning current impulse waveform<sup>[6-8]</sup> are shown as Fig. 1.

## 2 Test 1: single phase conduction/coupling test

**2.1 Test objective** When the N-line on the Y connection side of the test sample is impacted by lightning current, the conduction



**Fig. 1** Parameters of impulse lightning current waveform

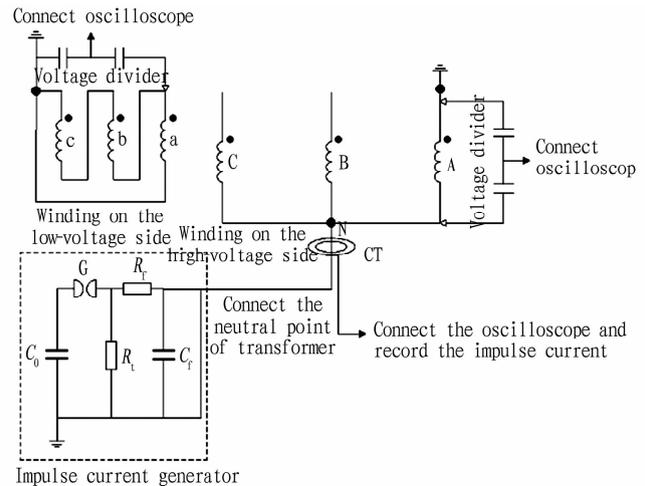
**2.2 Test method** The impulse current is input from the N terminal of high-voltage side, and the A, B, and C phases on the high-voltage side are separately grounded, while the corresponding c, a, and b terminals of low-voltage side are separately grounded. The oscilloscope collects the conduction voltage waveform parameters of each phase on the high-voltage side and the coupling voltage waveform parameters of corresponding phase on the low-voltage side. The positive and negative polarity of lightning current impacts three times each, and the wiring method is shown as Fig. 2.

**2.3 A-phase test** The impulse current is input from the N terminal of high-voltage side, with the A phase on the high-voltage side grounded separately and the C phase on the low-voltage side grounded. The oscilloscope collects the waveform parameters of A phase on the high-voltage side and the corresponding a phase on the low-voltage side.

**2.3.1 Parameters of A-phase test.** Positive and negative polarity of impulse current is conducted for three times, and A-phase test parameters are shown as Table 2.

**2.3.2 Waveform of A-phase test.** Waveform of A-phase test is shown as Fig. 3.

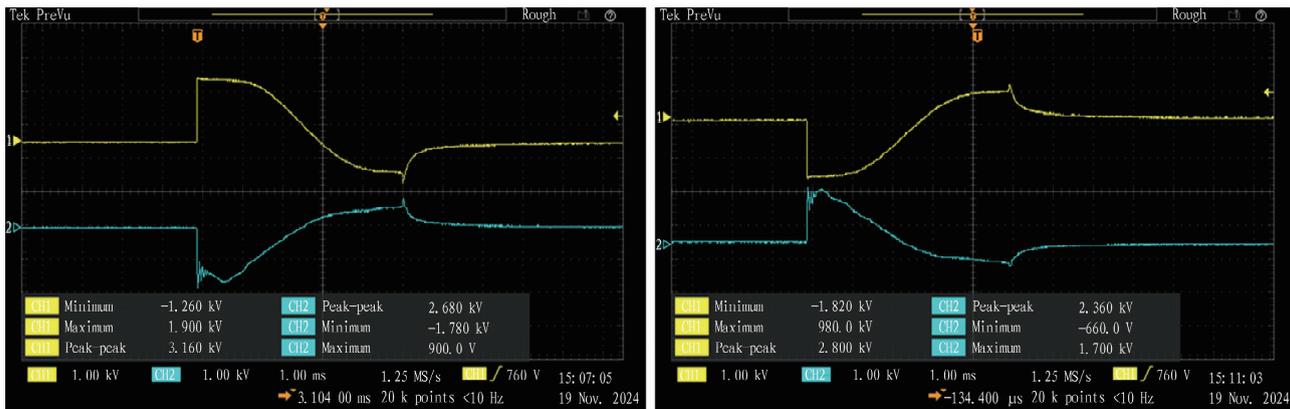
voltage waveform parameters of winding on the Y connection side and the coupling voltage waveform parameters of corresponding winding on the  $\Delta$  connection side are recorded, and their relationship is analyzed. The waveform parameter changes of corresponding windings on the high and low voltage sides of box-type transformer during the single-phase short circuit of collector circuit are simulated<sup>[9]</sup>.



**Fig. 2** Wiring for single-phase conduction/coupling test

**Table 2** A-phase conduction and coupling waveform parameters

Current polarity	Impulse current//kA	Impact position	Collection location	Maximum kV	Minimum kV	Collection location	Maximum kV	Minimum kV
Positive	4.81	N	A	1.90	-1.26	a	-1.78	0.90
Positive	4.81	N	A	1.86	-1.18	a	-1.74	0.78
Positive	4.81	N	A	1.86	-1.22	a	-1.70	0.90
Negative	-4.12	N	A	-1.82	0.98	a	1.70	-0.66
Negative	-4.12	N	A	-1.80	1.08	a	1.72	-0.80
Negative	-4.12	N	A	-1.84	1.00	a	1.68	-0.68



Note: a. Positive; b. Negative. CH1 shows the A-phase waveform, and CH2 shows the a-phase waveform.

**Fig.3** Waveform of A-phase test

## 2.4 Summary

(1) The conduction voltage waveform of each phase on the Y connection side is the same as the polarity of lightning impulse current, while the coupling voltage waveform of each phase on the  $\Delta$  connection side is the opposite to the polarity of lightning impulse current.

(2) The conduction voltage waveform of each phase on the Y connection side and the coupling voltage waveform of each phase on the  $\Delta$  connection side have the same amplitude, and the waveform envelope changes uniformly.

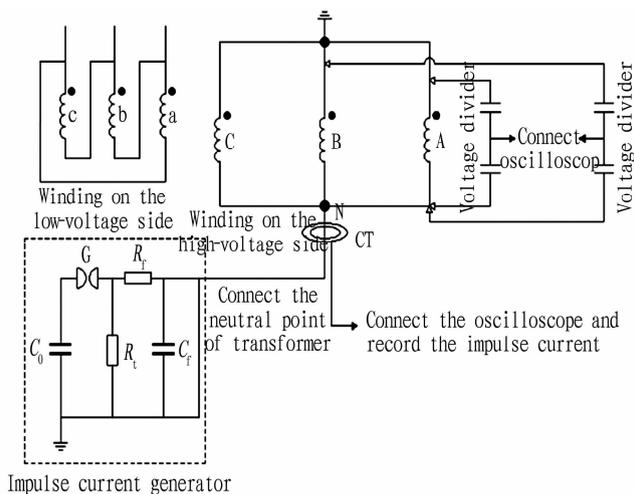
(3) The amplitude ratio of the coupling voltage waveform on the  $\Delta$  connection side to the conduction voltage waveform on the Y connection side is 1 : 1, which is not related to the transformation ratio of box-type transformer (the transformation ratio of this transformer is 1 : 1.815).

(4) The B- and C-phase test results are the same as those of the A-phase.

## 3 Test 2: three-phase grounding short-circuit conduction test on the Y connection side

**3.1 Test objective** When the N-line on the Y connection side is subjected to lightning current impact, causing a three-phase short circuit to ground, the waveform parameters between each winding are recorded<sup>[10]</sup>. The waveform parameters between the Y connection windings when the three phases of collection line are

simultaneously short circuited to ground are simulated. The test method and wiring are shown as Fig. 4.



**Fig.4** Three-phase grounding conduction test on the high-voltage side

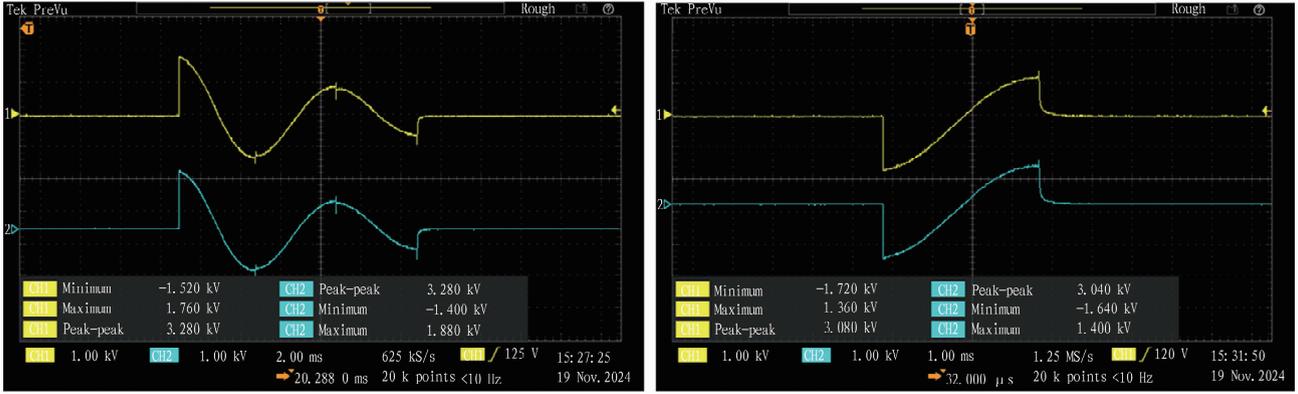
### 3.2 A – B-phase test

**3.2.1** Parameters of A – B-phase test. Positive and negative polarity of impulse current is conducted for three times, and A – B-phase test parameters are shown as Table 3.

**3.2.2** Waveform of A – B-phase test. Waveform of A – B-phase test is shown as Fig. 5.

**Table 3** A – B-phase conduction and coupling waveform parameters

Current polarity	Impulse current//kA	Impact position	Collection location	Maximum kV	Minimum kV	Collection location	Maximum kV	Minimum kV
Positive	4.81	N	A	1.76	-1.52	B	1.88	-1.40
Positive	4.81	N	A	1.80	-1.76	B	1.88	-1.60
Positive	4.81	N	A	1.76	-1.68	B	1.84	-1.56
Negative	-4.12	N	A	-1.72	1.36	B	-1.64	1.40
Negative	-4.12	N	A	-1.80	1.36	B	-1.72	1.40
Negative	-4.12	N	A	-1.76	1.44	B	-1.68	1.48



Note: a. Positive; b. Negative. CH1 shows the A-phase waveform, and CH2 shows the B-phase waveform.

Fig.5 Waveform of A – B-phase test

### 3.3 Summary

(1) When the three phases on the Y connection side are grounded and short circuited simultaneously, the polarity of conduction voltage between any two phases on the Y connection side of box-type transformer is the same as that of lightning impulse current.

(2) The phase of conduction voltage between any two phases on the Y connection side is the same, and the waveform envelope changes uniformly.

(3) The amplitude of conduction voltage among the three windings on the Y connection side is 1 : 1.

(4) The A – C-phase test results are the same as those of the A – B-phase.

## 4 Test 3: three-phase grounding short-circuit coupling test on the Y connection side

**4.1 Test objective** When the N-line on the Y connection side is subjected to lightning current impact, causing a three-phase short circuit to ground, the coupling waveform parameters between the  $\Delta$  connection winding and the corresponding winding on the Y connection side are recorded. The waveform parameters between the corresponding windings on the high and low voltage sides of box-type transformer when the three phases of collection line are

simultaneously short circuited to ground are simulated. The test method and wiring are shown as Fig. 6.

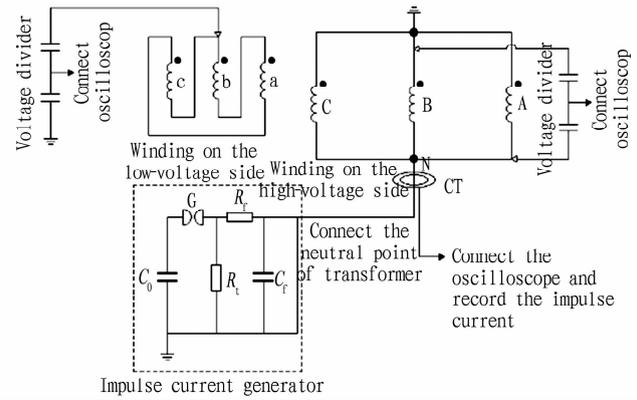


Fig.6 Three-phase grounding coupling test on the Y connection side

### 4.2 B – b-phase

**4.2.1 B – b-phase test parameters.** Positive and negative polarity of impulse current is conducted for three times, and B – b-phase test parameters are shown as Table 4.

**4.2.2 Waveform of B – b-phase test.** Waveform of B – b-phase test is shown as Fig. 7.

Table 4 B – b-phase conduction and coupling waveform parameters

Current polarity	Impulse current//kA	Impact position	Collection location	Maximum kV	Minimum kV	Collection location	Maximum kV	Minimum kV
Positive	4.81	N	B	1.76	-1.68	b	1.28	-1.08
Positive	4.81	N	B	1.64	-1.44	b	1.24	-0.92
Positive	4.81	N	B	1.76	-1.36	b	1.28	-0.88
Negative	-4.12	N	B	-1.52	1.36	b	-1.28	0.96
Negative	-4.12	N	B	-1.48	1.28	b	-1.00	0.92
Negative	-4.12	N	B	-1.60	1.12	b	-1.08	0.80

### 4.3 Summary

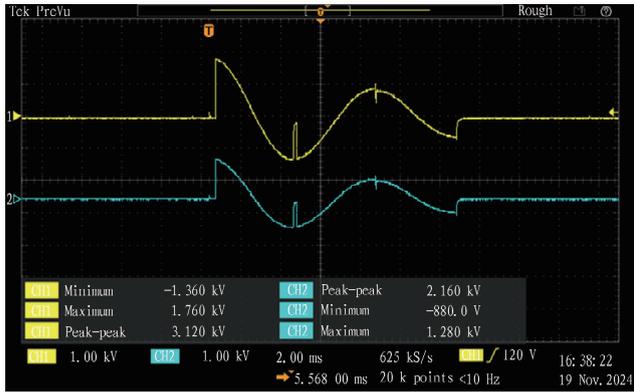
(1) When the N-line on the Y connection side is subjected to lightning current impact, causing a three-phase short circuit to ground, the coupling waveform polarity between the  $\Delta$  connection

winding and the corresponding winding on the Y connection side is the same as the polarity of impact current.

(2) The phase of coupling waveform between the  $\Delta$  connection winding and the corresponding winding on the Y connection

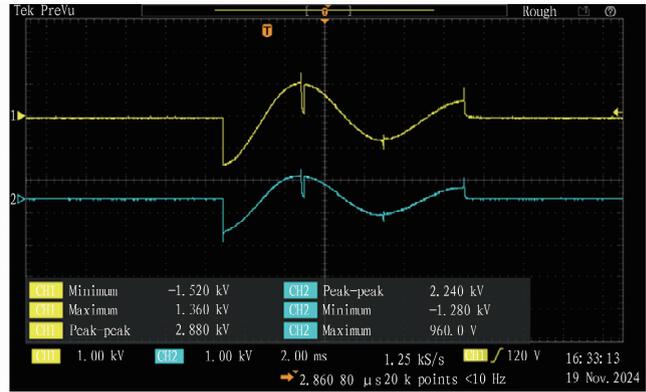
side is the same, and the waveform envelope changes uniformly.

(3) The amplitude ratio of coupling waveform between the  $\Delta$  connection winding and the corresponding winding on the Y connection side is 1 : 1.4 (the transformation ratio of input from same name end of primary and secondary windings of test sample is



1 : 1.8, while the input from different name end leads to a decrease in magnetic flux. Different transformer capacities have different amplitude ratios).

(4) The test results of A - a and C - c phases are the same as those of B - b phase.



Note: a. Positive; b. Negative. CH1 shows the B-phase waveform, and CH2 shows the b-phase waveform.

Fig.7 Waveform of B - b-phase test

## 5 Conclusions

(1) The lightning overvoltage waveform of primary and secondary windings of transformer has significant characteristics. The experimental data shows that the overvoltage waveform of primary and secondary windings of transformer has the following significant characteristics when lightning current invades the N-line of transformer. ① When there is a single-phase short circuit on the Y connection side, the conduction overvoltage waveform of each phase on the Y connection side and the coupling overvoltage waveform of each phase on the  $\Delta$  connection side have the same amplitude and opposite phase, and the amplitude of overvoltage of primary and secondary windings is independent of the transformation ratio. ② When there is a three-phase short circuit on the Y connection side, the polarity of coupling overvoltage waveform between the  $\Delta$  connection winding and the corresponding winding on the Y connection side is the same as the polarity of impulse current, and the phase is also the same. The waveform envelope changes in a consistent manner, and the amplitude ratio is 1 : 1.4, which is related to the transformation ratio. ③ Regardless of whether a single-phase short circuit or a three-phase short circuit occurs on the Y connection side, the lightning overvoltage on the primary and secondary three-phase windings of box-type transformer exhibits a symmetrical distribution pattern of three-phase overvoltage pulse<sup>[11]</sup>.

(2) Experimental data can be applied to fault analysis of relay protection. The wind farm has installed circuit breakers on each 35 kV line, and the operation of circuit breakers is mainly driven by current voltage protection and current quick break protection signal. In order to distinguish the interval where lightning accidents occur (high or low voltage side of main transformer), directional (impedance) relays are also equipped. Due to the sig-

nificant influence of geographical environment, line impedance, and weather changes, directional relays are prone to misjudgment<sup>[12]</sup>. This experimental data shows that the waveform of lightning overvoltage has significant polarity, phase, amplitude, and transformation ratio characteristics, and the interval position of lightning strike point can be easily analyzed from the fault waveform chart.

(3) It provides a new approach for analyzing the causes of lightning induced tripping in high-voltage transmission lines. Usually, people believe that it will not damage equipment after lightning enters the ground<sup>[13]</sup>. In fact, it could generate high potential on metal components such as grounding body after lightning enters the ground<sup>[14-16]</sup>, causing damage to electrical and electronic equipment in a certain area<sup>[17-18]</sup>. This test data indicates that when lightning current invades the N-line of transformer, it could generate conduction overvoltage in each winding on the Y connection side of transformer and coupling overvoltage in each winding on the  $\Delta$  connection side. When the value of lightning current invading the N-line of transformer is large enough, it could cause the 35 kV line circuit breaker to trip. The physical characteristics of this experimental data are applicable to any type of transformer with Y connection (including wind turbine box transformers and main transformers), providing new ideas for fault analysis of lightning tripping in high-voltage transmission lines.

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