Harmful effects of lightning surge discharge on communications terminal equipments

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Abstract. The interference problem of lightning surges on electronic and telecommunication products were examined, and a series of experiments were conducted to analyze the failure situations to find out the mechanisms of failures caused by the lightning surge. In addition, the ways in which lightning surges damaged equipment were deduced. It was found that failure positions were scattered and appeared in groups, and most of them were ground discharge. Internet access transformer had high withstand-voltage under the lightning pulse, and the lightning surge seldom passed through the internet access transformer. The lightning current can release to the ground via the computer network adapter of the terminal user. The study will help to improve the performance of lightning surge protection circuit and protection level.

1. Test method and equipment needed

With the increasing popularity of the electronic and telecom products, information communication is playing an increasingly significant role in our daily life and the development of the society. However, since the destruction of electromagnetic interference in the environment, especially the damage from lightning surge, which is of high voltage, large current, and instantaneity, the devices are in danger of communication interruption and blast fault which lead to serious accidents [1].

1.1 Test method

The lightning surge experiments can establish a common basis with the power lines, input/output lines and the telecommunication lines of the evaluation devices, when they are subjected to the high-energy pulse. As illustrated in the two figures, coupling and decoupling networks between the differential and the common mode tests are different. Coupling capacitance in the differential mode is 18 μF, while coupling capacitance in the common mode consists of a 9 μF capacitor and a 10 Ω resistor in series.

1.2 Experimental equipment and tested object

The YD/T993—2006 principle describes two different waveform generators, each has its own special applications according to the type of the tested ports. One kind of wave generators with ports connected to the symmetry of telecommunication lines is the 10/700 μS combination wave generator,

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and for other conditions, especially for those connected to the power lines and short distance signal interconnect ports, are the 1.2/50 μS combination wave generators.

Figure 1. Lightning surge on the single-phase power line of the differential mode immunity test.

Figure 2. Lightning surge on the single-phase power line of the common mode immunity test.

DSL, which is short for Digital Subscriber Line, is adopted in the experiments. It is a peer-to-peer transmission technology with the transmission medium of copper phone lines, which is generally known as xDSL including HDSL, SDSL, VDSL, ADSL, and RADSL. In the experiment we selected ADSL, which is a kind of new data transmission mode [2], as the tested object. It is called as asymmetric digital subscriber line because of the asymmetry between ascending and descending bandwidth.

2. Research on lightning surge effect

2.1 Lightning failure phenomenon
The experiments mainly analyzed the situation of burnout in large areas caused by lightning surge, and showed preliminary analysis results for typical lightning failure. The distribution of the most serious
damaged parts is shown in table 1. As can be seen, a large area of the PCB is burnout and one of the most typical cases is BCM6338 and BCM6301 chip failure.

**Table 1. Statistical machine failure.**

| Failure parts | U203(FLASH) | T401(LAN Components) | PCB | U401(BCM6301) | U101(BCM6338) |
|---------------|-------------|----------------------|-----|---------------|---------------|
| Breakdown number | 25          | 32                   | 41  | 72            | 279           |

2.2 **Withstand voltage test and current path analysis in the key components**

2.2.1 **Withstand voltage in ADSL transformer test and analysis.**

Table 2 shows the withstand voltage test parameters of five ADSL transformers. As can be seen from the table, three samples have no significant changes in it, which indicates that high-voltage pulses pass into the lower-level circuit through ADSL transformer. We find that the value of the insulation resistance of the transformer in network port doesn’t reduce in a damaged machine. However, for the fourth and fifth sample (1# sample, 2# sample retested respectively), when using a long rise time (25 s) in the test, the leakage current is less than 3.5 mA. The result demonstrates that the transformer doesn’t breakdown under that voltage, and the leakage current in the first three samples is generated because the increasing high frequency components in voltage lead to distributed capacitance coupling with the coil resistance in a very short rise time.

Then we replaced the ADSL transformer with a 35 pF/3 kV capacitor connecting between the first level and the second level of ADSL transformer in TX and RX channel to simulate distributed capacitance of the ADSL transformer, respectively. The circuit worked normally when the voltage ranged from 5 kV to 9 kV. This indicates that the energy from equivalent capacitance (35 pF) between the first level and the second level of ADSL transformer coupling to lightning pulse can't damage TVS pipe or other circuits.

**Table 2. Voltage test of the ADSL transformer.**

| Num / Type | Maximum voltage | Rise/hold time | Leakage current | Retest voltage | Resistance |
|------------|-----------------|----------------|-----------------|----------------|------------|
| 1# / MT5422 | 5500 V          | 0.1 s/10 s     | >3.5 mA         | >5000 V        | >10e+9 Ω   |
| 2# / MP9042 | 6000 V          | 0.1 s/10 s     | >3.5 mA         | >5800 V        | >10e+9 Ω   |
| 3# / MP9042 | 6000 V          | 0.1 s/10 s     | >3.5 mA         | >5800 V        | >10e+9 Ω   |
| 4# / MT5422 | 5500 V          | 25 s/10 s      | <3.5 mA         | ——             | >10e+9 Ω   |
| 5# / MP9042 | 6000 V          | 25 s/10 s      | <3.5 mA         | ——             | >10e+9 Ω   |

Tables 3 can be drawn when lightning tests are carried out in different ADSL transformers. Analyzing the phenomenon of table 3, we know that when lightning pulses pass through the ADSL transformer, the energy transfers through air discharge between the primary and the secondary transformer rather than capacitive coupling.

However, air discharge is a complex process. In a uniform electric field, breakdown voltage can be up to a maximum of 30 kVcm⁻¹ when air space is more than 1 cm; while in the non-uniform electric field, the breakdown voltage between the gas gaps drops [3], which is closely related to the two electrode surface shapes of air gap formation. Specifically, the smaller the curvature radius of the electrode is, the higher probability of the point discharge will be, and the lower the value of breakdown voltage will be [4].
Different point discharges for different discharging voltages, and the tests indicates that the minimum voltage 3.9 kV can generate discharge. The discharge of the transformer under the high voltage between first level and second level causes the explosion.

**Table 3. Lightning current test of different ADSL transformers.**

| Test sample | ADSL transformer(2 kV) | ADSL transformer (5 kV) |
|-------------|------------------------|-------------------------|
| Test conditions | All pins in the primary and the secondary transformer were short circuit, respectively. The 75 Ω resistance and the transformer were in series and the voltage increased from 3 kV to 6 kV. | All pins in the primary and the secondary transformer were short circuit, respectively. The 75 Ω resistance and the transformer were in series and the voltage increased from 5 kV to 9 kV. |
| Test phenomenon | The transformer worked normally as well as the resistance when the voltage was less than 6 kV, however, the transformer blasted when the voltage was larger than 6 kV. The value of the resistance increased. (>100Ω) | The transformer worked normally as well as the resistance when the voltage was less than 9 kV, however, the resistance got to an open circuit and blasted when the voltage was larger than 9 kV. |

2.2.2 Internet access high voltage capacitor test and analysis.

Experiments about lightning tests on high voltage capacitor were performed. From the experiments we know, for a 1000 pF capacitor, it works well while transient current passes through and the internet access resistance blasts when the lightning surge voltage is about 2500 V. The value of the insulation resistance will reduce if the internet access transformer is breakdown. However, it never happens in the damaged devices, which indicates a low probability of the lightning surge going through internet access transformer. Table 4 and table 5 show the experiments about lightning test on high voltage capacitor with 0603 resistance in series connection. The test voltage ranges from 2 kV to 5 kV and the capacitor works well until the test voltage reaches 5000 V.

**Table 4. Lightning test of the high voltage capacitor (1000 pF /3 kV).**

| Test voltage | 2000V | 2500V | 3000V | 3500V | 4000V |
|--------------|-------|-------|-------|-------|-------|
| Resistance value | normal | 84Ω | 106Ω | 3.23KΩ | 39.8KΩ |
| Capacitor value | normal | normal | normal | normal | normal |

**Table 5. Lightning test of the high voltage capacitor (1000 pF /2 kV).**

| Test voltage | 2000 V | 2500 V | 3000 V | 3500 V | 4000 V | 5000 V |
|--------------|--------|--------|--------|--------|--------|--------|
| Resistance value | normal | 77.2Ω | 78.4Ω | 78.1Ω | 84.4Ω | Burn out |
| Capacitor value | normal | normal | normal | normal | normal | Burn out |

If we assume the rise time for the lightning pulse is 1.2 μs, and the frequency can be described as:

\[ f = \left( \frac{\pi r}{C} \right)^{-1} \]  

(1)

The derived frequency is about 265 KHz. And the equivalent impedance is:

\[ Z_e = \left( 2\pi f C \right)^{-1} \]  

(2)
If we assume the capacity of the high-voltage capacitor is 1000 pF, and the derived impedance is 525 Ω. Therefore, the equivalent resistance from ground to internet access is:

\[ Z_0 = Z_c + Z_R \approx 600 \] (3)

Capacitor will not have breakdown when high voltage surge is lower than it’s withstand voltage capacity, but it couples with the 75 Ω matching resistance and discharges to ground through internet access. When the voltage is 2500 V, the transient current is estimated about 4 A. If this current is regarded as the resistance current, transient voltage can reach 300 V. It largely exceeds the rated voltage (50 V) of 0603 resistance, so the resistance is damaged.

The last test was the lightning surge in the combination model of the key components. The test circuit composed of a 2 kV ADSL transformer, a 1000 pF/2 kV capacitance and a 75 Ω resistance in series connection. The resistance worked normally when the voltage was less than 8.5 kV, however, the capacitance burned out when the voltage became even larger. We knew that there was no current in the circuit before the air discharge of the ADSL transformer [5]. The 1000 pF/2 kV capacitance broke down and the resistance burned out as long as the ADSL transformer discharged. And it never happened that the 75 Ω resistance burned out while capacitance worked normally in the process of the ADSL transformer discharge. There is no obvious relationship between the withstand voltage of the ADSL transformer and the resistant of the lightning surge effect [6]. But the withstand voltage of the internet access transformer is closely related to the resistant and higher withstand voltage in high voltage capacitance results in a better effect in resisting lightning surge.

3. Conclusions
One of the most significant tasks of researching lightning discharge failure is to determine the discharge route, which plays a key role in improving the design of the discharge protection circuit [7]. To analyze the influences of lightning surge to the electronic and telecom products, a series of experiments were performed. The following conclusions were drawn from the experiments:

(1) The failure positions were scattered and appeared in groups, and most of them were ground discharge;
(2) Lightning surge imported from telephone port and the current went through the way of air discharge into the ADSL transformer. Finally it coupled with the ADSL transformer of the subprime circuit;
(3) Internet access transformer had high withstand-voltage under the lightning pulse, and the lightning surge seldom passed through internet access transformer;
(4) After the current passed the AFE chip, the internet access matching resistance coupled with the large value capacitance. Because of the capacitance coupling, the lightning current passed through and then released to the ground via the computer network adapter of the terminal user.

According to the failure analysis, the paper deduced the discharge route of lightning surge which could provide some guiding significance for the design of lightning surge protection circuit and make a further contribution to improving the protection level.

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