Ungrounded Lightning Surge Protection Device for Wireless Sensor Networks Node in the Wilderness

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***Abstract*—The maintenance free remote monitoring character of wireless sensor networks (WSN) node in the wilderness demands ungrounded lightning surge protection. In this paper, a protection device with functions of low frequency surge cutting off and RF signal passing is designed, in which discharge circuit consists of three-level surge by-pass circuit, the antenna outer conductor and the circuit board copper clad. The current capacity, the start time and the output voltage meet the requirements of surge protection for weak current device. The discrete components that undertake protective effect were involved in impedance matching calculation. The parameters of discrete components were estimated and adjusted constantly at test stage to insure the inserted protection device impedance matching with the node RF transceiver module and antenna. The experimental results show that the node with the ungrounded protection device can pass the fourth level surge immunity experiments and have run of 49 months in Xinjiang coal fire area outdoor monitoring site.**

Keywords—lightning surge protection; ungrounded; wireless sensor networks; impedance matching;

I. Introduction

Lightning protection is an important content in EMC (Electromagnetic Compatibility) research, among which heavy electricity protection devices have a hundred years of development history and more mature technology [1–4]). With the development of large-scale integrated electronic systems, lightning protection related to the weak electricity devices start from a few decades ago and have different protective devices and specifications of various applications [5–8]. The wireless sensor networks (WSN) node deployed in the wilderness, with low-voltage, low-power and high-frequency, is a very special weak electricity device, which requires the protection device with quick response, low output voltage and large current capacity. Communications character and free maintenance character of WSN node requires that the protection device does not affect the transmission of signals and does not include the grounded device that must be maintained. To date, most existing protection devices are grounded [9-10], and some ungrounded protection circuits have otherwise applicable scope in the aspects of starting voltage, response speed and current capacity [11-12]. This paper designed an ungrounded lightning protection device, which consists of series circuit and three levels shunt circuit [13]. The transfinite surge energy pass through discharge circuit formed by three-level discharge passage, copper clad and antenna outer conductor, neutralizing induced charge. The characteristic impedance and import impedance are matching with antenna and RF transceiver module of 2.4 GHz WSN node [14]. The minimum return loss, the voltage standing wave ratio (VSWR) and the insertion loss were −20.9 dB, 1.198 and − 0.9 dB respectively, and achieved requirements specified in IEC Standard 62305-1[7]. The results of surge immunity test and the field test show that the ungrounded protection device for the WSN node can defend against kilovolt\ kilo-ampere lightning surge.

II. Performance Requirements of Lightning Surge Protection Device

The lightning effects include direct lightning and induction lightning. The former have strong damage ability and small occurrence probability, and the latter have high occurrence probability and large impact scope [15]. In the international standard IEC 61000-4-5[16], the time waveform of surge caused by induction lightning can simulate with the combined wave of 1.2/50 μs – 8/20 μs, which rises to the withstand value of weak electricity device about several nanosecond. Frequency spectrum and energy concentrate in the low frequency from 0 Hz to 100 kHz.

For the WSN nodes deployed in the wilderness, antenna exposed to the air can receive signal, and also easily have the risk of the lightning surge. Therefore, the protection mainly focused on the antenna feeder system. As shown in Table Ⅰ, the surge protection circuit should have many technical indicators to meet the industry standards [8].

TABLE I. Technical Indicators of Surge Protection Device

Parameter	Requirement
Operating frequency	2.4GHz
Current capability	kA
Voltage capability	kV
Response time	ns
Transmission power	≥1.5×node power
Voltage standing wave ratio	≤1.2
Insertion loss	≥-1dB
Impedance characteristic	50Ω

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III. LIGHTING SURGE PROTECTION CIRCUIT

The surge protection circuit designed consists of series and shunt part, as shown in Fig.1. The series circuit, a signal line with capacitance C_1 between antenna and node RF module, cut off LF surge and transit RF signal. Shunt part is composed of gas discharge tube (GDT), metal oxide varistor (MOV) and transient voltage suppressor (TVS). The output voltage, the current capacity and startup time of three levels decline in turn. By these three channels, the antenna signal line and the antenna outer conductor forms a discharge circuit. Inductance L_1 and L_4 separate signal line from the surge discharge channel.

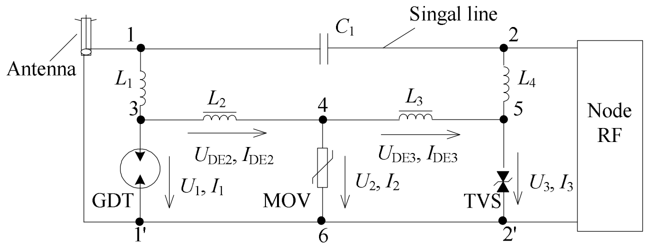


Fig. 1. Principle diagram of antenna feeder surge protection circuit

A. Operating principle of circuit

When LF surge arrive, capacitor C_1 is equivalent to open circuit and inductance L_1 is equivalent to short circuit. Surge voltage added on port 1–1′ rises quickly, then TVS conduct firstly and output voltage of it is less than the tolerance voltage of WSN node. The conduction path between ports 1–1′ is through 1–3–4–5–2′–1′. As the current of port 1–1′ increase, the inducted dynamic voltage U_{DE3} by inductance L_3 raise. If the superposition value of U_{DE3} and TVS clamp voltage U_3 is greater than MOV open voltage, the secondary channel starts to discharge. As well，if the induced dynamic voltage U_{DE2} with the addition of MOV clamping voltage U_2 is greater than the starting voltage of GDT, the first main discharge channel put through and discharge to the circuit board copper clad and form a loop with antenna line outer conductor.

B. Determine component types and parameters

In according with the work principle of the protection circuit, the coordination principle at all levels and the electrical characteristics of the node, ESD5B5.0ST1G type TVS, 20D180K type MOV and A81-C90X type GDT [17-19] was selected.

From Fig. 1, it can be see that GDT discharge depends on whether the sum of U_2 and U_{DE2} is greater than GDT discharge voltage U_S:

$$\begin{aligned} U_1 &= U_2 + U_{DE2} > U_S \\ U_{DE2} &= L_2 \cdot \mathrm{d}I_{DE2}/\mathrm{d}t \end{aligned} \tag{1}$$

For 8/20 μs surge waveform with 1 kA peak, $\mathrm{d}I_{DE2}/\mathrm{d}t$ is about 0.1 kA/μs. U_2 is 36 V [18], and U_S is 600 V [19]. We can obtain that GDT can be pushed when L_2 > 5.64 μH. In order to leave some margin, inductance L_2 is set as 10 μH. By the same method, inductance L_3 is set as 12 μH.

In RF band, inductance L_1 and L_4 segregate signal line from discharge channel. Capacitance C_1 and resistance R (50 Ω) of WSN node constitute the RC high-pass filter. The voltage ratio between output and input is:

$$\dot{A} = \frac{R}{R + 1/j\omega C_1} = \frac{1}{1 + 1/j2\pi f RC_1} \tag{2}$$

Cut-off frequency is defined as: $f_L = 1/2\pi RC_1$. In order to pass RF signal (2.4 GHz – 2.4835 GHz), f_L should less than 2.4 GHz, and so C_1 > 1.3 pF. Considering the distribution capacitance of circuit, C_1 was set as 5 pF. Measured by digital electric bridge, the equivalent capacitance of the transmission line is 1.5 pF, which is similar to the theoretical estimate.

C. Impedance matching

In this paper, the discrete component of protection device also undertakes function of impedance matching. For the RF signal, L_2 and L_3 are equivalent to open circuit, and Fig. 1 can be equivalent to Fig. 2.

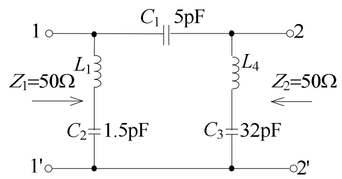


Fig. 2 Impedance matching equivalent circuit of antenna feeder port.

Where, C_2 and C_3 are the stray capacitance of GDT and TVS. The equivalent impedance Z_1 of port 1–1′ and Z_2 of port 2–2′ respectively equal to the characteristic impendence of antenna and WSN node, which are defined as [20]:

$$Z_1 = \sqrt{Z_{oc1} Z_{sc1}},\ Z_2 = \sqrt{Z_{oc2} Z_{sc2}} \tag{3}$$

Where Z_{oc1} or Z_{sc1} are the equivalent impedances of port 1–1′ when port 2–2′ is open-circuit or short-circuit; Z_{oc2} or Z_{sc2} are the equivalent impedances of port 2–2′ when port 1–1′ is open-circuit or short-circuit:

$$\begin{aligned} Z_{oc1} &= \left(j\omega L_1 + 1/(j\omega C_2)\right) // \left(1/(j\omega C_1) + j\omega L_4 + 1/(j\omega C_3)\right) \\ Z_{sc1} &= \left(j\omega L_1 + 1/(j\omega C_2)\right) // \left(1/(j\omega C_1)\right) \\ Z_{oc2} &= \left(j\omega L_4 + 1/(j\omega C_3)\right) // \left(1/(j\omega C_1) + j\omega L_1 + 1/(j\omega C_2)\right) \\ Z_{sc2} &= \left(j\omega L_4 + 1/(j\omega C_3)\right) // \left(1/(j\omega C_1)\right) \end{aligned} \tag{4}$$

Where Z_1 = 50 Ω, Z_2 = 50 Ω, C_1 = 5 pF, C_2 = 1.5 pF [19], C_3 = 32 pF [17], ω = 2π × 2.4 GHz, we substitute these parameters into (3) and (4), and obtain that: $L_4 \approx 5.4$ nH，$L_1 \approx 151$ nH.

D. Ungrounded design

This device is designed for low - grade lightning surge. The protection device PCB except lines and the RF signal channel area is covered with copper-clad in both sides, which are connected by via holes array to increase the volume. The thickness of copper foil with 140 μm is 4 times the ordinary

PCB, which improves the capacity of holding electric charge as a buffer pool.

IV. Performance Test

Follow the above analysis, the ungrounded lightning surge protection device was made and tested corresponding to the performance indicators in Table Ⅰ.

A. Parameters measurement

The S11 curve of surge protection boards measured by vector network analyzer is shown in Fig. 3. The center frequency 2.43 GHz is in the frequency band of WSN node; the minimum value of S11 is −20.9 dB that approaches the minimum value of antenna; −10 dB bandwidth (2.39 GHz – 2.50 GHz) cover the frequency band of WSN node (2.4 GHz – 2.4835 GHz). In according with the minimum S11, the VSWR is calculated as 1.198. Under the impedance matching conditions of the port, the S21 parameter can represent insertion loss. The S21 was measured by the vector network analyzer, and it was obtained that the insertion loss at 2.43 GHz is – 0.9 dB. All of these parameters meet performance indicators in Table Ⅰ.

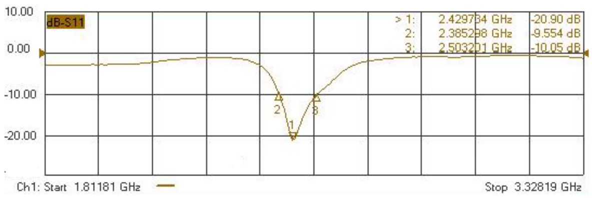
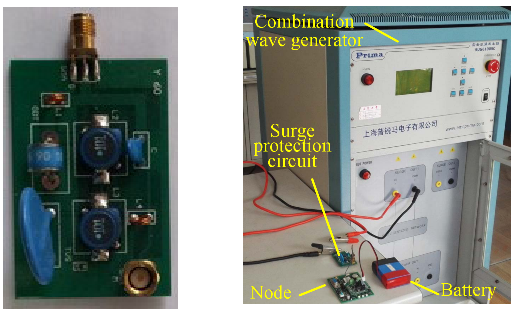


Fig. 3. S11 parameter curve of surge protection device

B. Surge immunity test

As stipulate in international standard IEC 61000-4-5, we set the experimental conditions and test procedure. The surge protection device (Fig. 4a) was connected with the surge immunity test equipment (Fig.4b) and tested from level 1 to level 4 for many times. The result is they pass the level 4 test.



(a) (b)

Fig. 4. (a) Surge protection device. (b) The connection diagram of surge protection device with immunity test equipment.

V. Conclusion

The protection circuit designed for WSN node bypasses LF surge and passes the high frequency signal. Three-level protection components of by-pass circuit cooperate in start time and energy. When the by-pass circuits are conducting successively, the RF signal line and outer conductor of antenna form closed loop through TVS, MOV and GDT. This loop can consume surge energy, and the thickness of copper foil of PCB can improves the capacity of holding electric charge as a buffer pool, so the discharge circuit lines can withstand surge energy. The experimental results show that the node with the protection device can pass the standard level 4 of the surge immunity test. The device, applied to the Xinjiang coalfield fire monitoring network, make the network monitoring work safely and continuously for 4 thunderstorm seasons. If we change the types and the parameters of the components, and adjust the working frequency and the characteristic impedance, this ungrounded device could be used to protect the other weak current device.

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