Design of a Flexible Rogowski Coil with Active Integrator Applied in Lightning Current Collection

Yang Jun[#1], Guiting Li[#2], Huping Liu[#3], Guohua Yang[#4],Gong Ling[#5]
R&D Department, Sichuan Zhongguang Lightning Protection Techniologies Co.,LTD
No.19 Tianyu Road, West Park, Chengdu Hi-Tech Zone, Chengdu, Sichuan, P.R.China
[1]yangj@zhongguang.com
[2]liuhp@zhongguang.com

***Abstract*—**Rogowski coil has been applied widely in the field of lightning current measurement, because it has good linearity, no saturation phenomenon, as well as the electrical isolation between the primary side and secondary side. This paper mainly introduces three kinds of Rogowski coil applied in lightning current collection, and also analyzes and compares them with experiment. We can select the appropriate coil according to the different occasions, costs and installation form. This paper focuses on the application and design of flexible Rogowski coil with active integrator which is used in lightning current collection. The experimental result indicates that the active integrator has good linearity and waveform restoration, especially better integral effects on the frequencies from hundreds Hz to hundreds kHz.

***Keywords*—** Rogowski coil Active integrator Lightning Current Collection Linearity Waveform restoration

I. INTRODUCTION

In recent years, electronic current transformer based on Rogowski coil has wider application prospects than conventional electromagnetic current transformer. Its advantages include large dynamic range, wide frequency response and strong resistance to electromagnetic interference. Its unique structure avoids the problem of temperature and vibration that exist in the pure optical sensing head. Electronic current transformer based on Rogowski coil is the future direction of current transformer, which can adapt to development trend of digitalization and automation of electric measurement and relay protection. Rogowski coil is an effective tool to measure the strong impulse current because of its advantages of high precision, good stability, strong anti-interference capability, wide dynamic range and small size. It can measure the current of transformer, GIS, circuit breaker and PASS switch. Rogowski coil is also widely applies to the measurement of high power pulse technology.

The research of rigid and flexible transducers based on Rogowski coil has become hot at present. This paper analyzes and compares the rigid Rogowski coil, flexible Rogowski coil with ordinary RC passive integrator and flexible Rogowski coil with active integrator, respectively. The researches and problems in development of three kinds of coils are mainly illustrated by the experimental waveforms. In this paper, the experimental waveforms are obtained from 8/20μs impulse current generator, digital oscilloscope, PEARSON current monitor, 8/20μs compatible 10/350μs impulse current device.

II. INTRODUCE OF LIGHTNING CURRENT

Lightning is a strong discharge phenomenon between the thunderclouds or between a thundercloud and the earth formed in severe convection weather. It has high impulse current, high temperature, violent shock wave and strong electromagnetic radiation, which can damage the buildings, transmission line, outdoor equipment and result in casualty of the human and animal. Lightning has characteristics such as high voltage, large current, instantaneity and long distance.

Lightning current is a non-periodic transient current that usually soon roses to the peak and slow to fall. The impulse wave uses a combination of two values T1/T2 to illustrate. T1 is front time from 10% up to 90% of peak value. T2 is the time to half value on the tail of impulse current. These times use 'μs' as the unit marked with T1/T2. The standards of IEC and GB stipulate the lightning testing waveform such as 8/20μs, 10/350μs（current wave）, 10/700μs and 1.2/50μs（voltage wave）. For example, in 1.2/50μs impulse voltage, front time is 1.2μs, the time to half value is 50μs; in 8/20μs impulse current, front time is 8μs, the time to half value is 20μs; in 10/350μs impulse current, front time is 10μs, the time to half value is 350μs. Fig.1 is 8/20μs impulse current waveform.

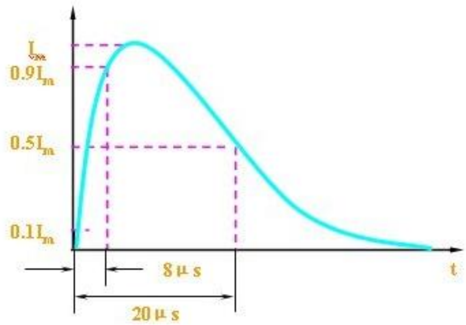


Fig.1 8/20μs impulse current waveform

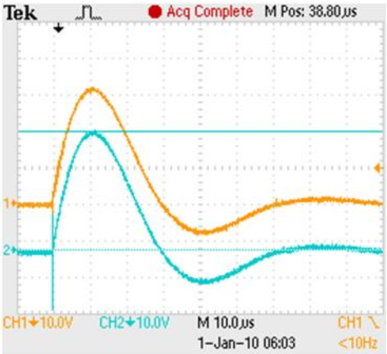
Lightning effects are divided into direct-lightning and lightning electromagnetic pulse (LEMP). Direct-lightning is characterized by 10/350μs. LEMP is characterized by 8/20μs. This provides a practical waveform verification basis for us to design and test the coil.

III. Comparison of Three Kinds of Rogowski Coil

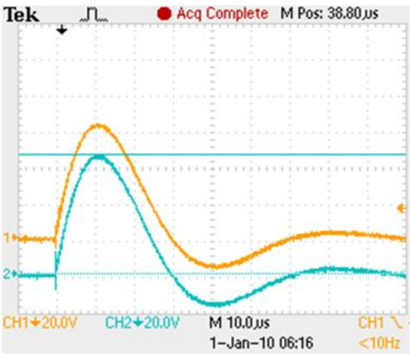
Three kinds of Rogowski coils are mentioned in this paper, they are rigid Rogowski coil, flexible Rogowski coil with passive integrator and flexible Rogowski coil with active integrator.

Rigid Rogowski coil uses magnetic material as skeleton to wind. Magnetic material with high magnetic conductivity is easy to satisfy the self-integral condition, so this coil uses the form of self-integral to restore the waveforms. Rigid coil is electromagnetic structure. But it has a large volume and heavy weight, in particular, its magnetic core is easy to generate magnetic saturation when a fault happens on the lines. It is hard to realize the measurement of wide range current. On the installation, the heavy rigid transducer with magnetic core can't fall or shake, and easy to be influenced by outside environment. It is not convenient to disassemble and installation, thus its application is limited. The result of experimental waveforms is shown in figure 2, CH1 is the waveform of PEARSON current monitor (1000 times), CH2 is the waveform of self-made rigid coil.

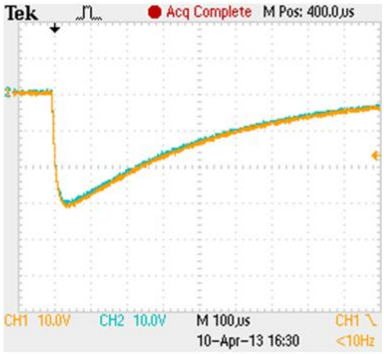
+30kA 8/20µs waveforms：



+60kA 8/20µs waveforms：



-30kA 10/350µs waveforms：



-50kA 10/350µs waveforms：

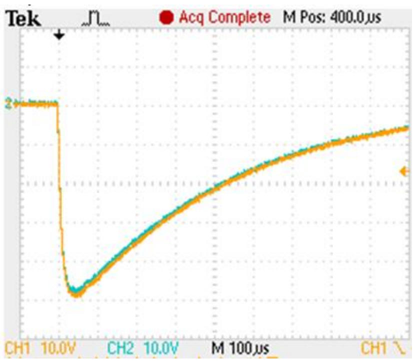
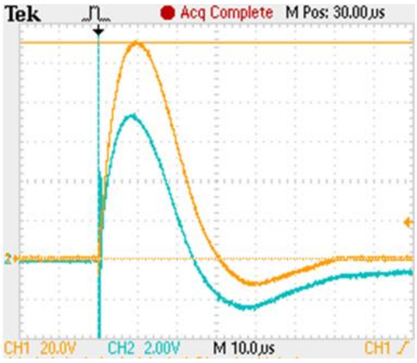


Fig.2 Experimental waveforms of rigid Rogowski coil

Flexible transducer is a new current transducer based on the Rogowski principle. It has such advantages as light weight, soft and pliable, complete isolation between the primary and secondary side, convenience to install and disassemble, large testing range (10A ups to 1000kA), wide dynamic range, low cost, good linearity, no magnetic saturation. According to the different integral methods, it is divided into passive integrator and active integrator.

Flexible Rogowski coil with passive integrator is winded in the non-magnetic material skeleton as same as the flexible Rogowski coil with active integrator, but they are different in integral methods. Rogowski coil with passive integrator adopts RC passive integrator with simple circuit structure. It can't simultaneously obtain the higher sensitivity and lower limit. Under the same sensitivity conditions, it can't lower the low frequency limit of integrator. Only when the integral time constant $RC >> T$ (signal period), it can obtain approximate integral effect, but with low output precision and small output amplitude, and it is adverse to improve the S/N ratio. The bandwidth of flexible Rogowski coil with passive integrator is not wide enough, it is not effective to transmit the transient current signal and easy to generate the waveform distortion at low frequency. The result of testing waveforms is shown in figure 3, CH1 is the waveform of PEARSON current monitor (100 times), CH2 is the waveform of flexible Rogowski coil with passive integrator.

+10kA 8/20µs waveforms：



-10kA 10/350μs waveforms：

Fig.3 Testing waveforms of flexible Rogowski coil with passive integrator

From the figures above we can see, flexible Rogowski coil with passive integrator is not good to restore the waveform of 8/20μs and 10/350μs, the time to return to zero is prolonged, and it causes the 10/350μs waveform distortion more seriously. But compared with the rigid Rogowski coil, flexible Rogowski coil with passive integrator is portable and flexible, and has the advantages of light weight, low cost and not being prone to magnetic saturation. However it is not better than rigid Rogowski coil in precision.

Considering the advantage-disadvantage and application environment of existing Rogowski coils, we design a flexible Rogowski coil with active integrator. Flexible Rogowski coil with active integrator uses high performance operational amplifiers to make up the analog integrator. When working at low frequency, passive integrator can't collect such weak output signals from coil(less than mV). However, active integrator can apply to collect the low frequency signal. The operational amplifier has advantages of high input impedance, high open-loop gain, virtual-short and virtual-cutoff, which can effectively guarantee the higher integral precision. The higher bandwidth and precision provided by active integral method can effectively restore the measured current waveforms. The comparison of three kinds of Rogowski coil is shown in table 1.

TABLE I Comparison of three kinds of Rogowski coil

Type	Integral form	Installation method	Range of frequency	Magnetic saturation
Rigid Rogowski coil	Self-integral	Down lead must be disassembled	200Hz~ 4MHz	Yes
Flexible Rogowski coil with passive integrator	conventional RC integral	No requirement for installation position	1kHz~ 4MHz	No
Flexible Rogowski coil with active integrator	active integral	No requirement for installation position	200Hz~ 6MHz	No

IV. THE DESIGN OF FLEXIBLE ROGOWSKI COIL WITH ACTIVE INTEGRATOR APPLIED IN LIGHTNING CURRENT COLLECTION

The working principle of flexible Rogowski coil with active integrator described in this paper is: differential signal of lightning current is obtained when transmission line passes through the flexible Rogowski coil of traveling-wave sensor, which is reverted to the current signal by integrator. Active integrator needs to be adapted to specific parameters of Rogowski coil, and the sensitivity of coil relates to the integral parameters of active integrator, which can be adjusted according to the relationship between the integral parameters and the coil.

The output of Rogowski coil is the differential signal of the lightning current. Fig.4 is an equivalent circuit diagram of Rogowski coil, ignoring the effect of the coil distributed capacitor.

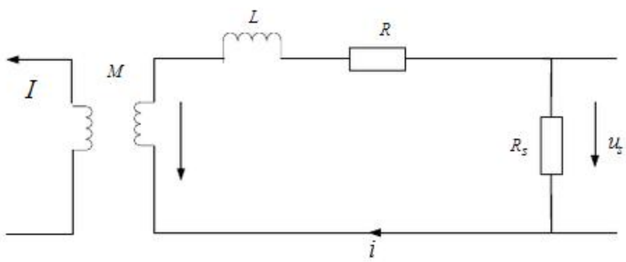


Fig.4 equivalent circuit

In fig.4, L is the self-inductance of Rogowski coil, M is the mutual-inductance of Rogowski coil, R is the internal resistance of Rogowski coil, I is the measured current, i is the current of Rogowski coil, u_i is the induced electromotive force, R_s is the sampling resistance, u_s is the sampling voltage.

According to the equivalent circuit of Rogowski coil, we have:

$$u_i = -M\frac{dI}{dt} \qquad (1)$$

$$u_i = L\frac{di}{dt} + (R + R_s)i \qquad (2)$$

When $L\frac{di}{dt} << (R + R_s)i$, simplify as:

$$I = -(R + R_S)/M\int \frac{u_i}{R_s}dt \qquad (3)$$

The conditions of Rogowski coil worked at exterior integrator is $L\frac{di}{dt} << (R + R_s)i$, that is the terminating sampling resistance $R_s >> R$, and $R_s >> \omega \times L$, where ω is the frequency of input signal. Because of the little internal resistance R of Rogowski coil, active integrator only needs the condition of $R_s >> \omega \times L$.

From equation 3 we have: a differential relationship exists between measured current I and sampling voltage u_i , that is, Rogowski coil and the sampling resistance R_s are substantially a differentiation element and an integrator is needed to integrate the voltage u_i , which can revert the output signal to the measured current.

The original lightning current signal can be restored by integrator. Fig.5 is the basic circuit of active integrator that consists of resistance R , capacitor C and OPA operational element. The principle of integrator is: from the virtual-short and virtual-cutoff principle of negative feedback circuit in operational amplifier, we have：

$$i = u_i / R, u_o = u_c = 1/C\int icdt$$

That is the current through the resistor integrated on the capacitor C . The precision of active integrator is based on the virtual-short and virtual-cutoff feature, the inverting input of operational amplifier has virtual-short feature: $i = u_i / R$, that ensures the accurate charging current of the capacitor, which is an important reason that active integrator has higher precision than passive one. By constrast, the charging current of capacitor with passive integrator will decrease with increasing voltage of capacitor, which can reduce the integral precision.

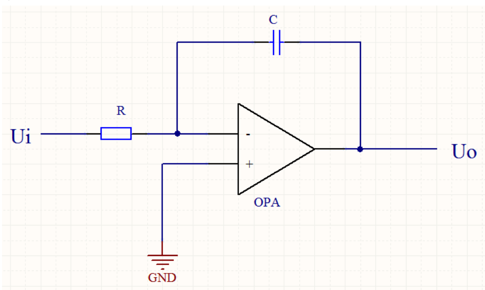


Fig.5 Basic circuit of active integrator

In the design of flexible Rogowski coil based on active integrator, the experimental circuit of practical active integrator is shown in fig.6.

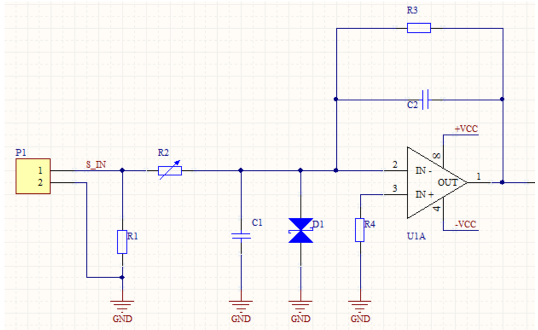


Fig.6 The experimental circuit of practical active integrator

Flexible Rogowski coil based on active integrator adopts flexible Rogowski coil with low cost and high performance as sensory package. Flexible Rogowski coil is made of flexible skeleton and enamelled wires, which is required to wound evenly based on one winding in the process of winding. Therefore, flexible Rogowski coil is not only to reduce the cost, but also to improve the sampling frequency, to eliminate saturation phenomenon and to increase reliability. Moreover, traveling-wave sensors of different amplitude can realize large range lightning current measurement so as to improve the positioning accuracy, reliability of device, and bandwidth limit.

In fig.6, $R1$ is sampling resistance, $R2$ is integral resistance, $C2$ is integral capacitor, $R3$ is discharge resistance used to stable the low frequency gain and restrain the output drift of operational amplifier which leads the output saturation of operational amplifier. $U1$ is high performance operational amplifier, $C1$ is a small capacitor of pF grade that is used to filter the high-frequency noise of coil, $D1$ is transient voltage suppressor that is used to protect the operational amplifier from lightning-striking damage, $R4$ is balance resistance of operational amplifier that is used to reduce the offset voltage from the output caused by the bias current of operational amplifier, $P1$ is connecting socket of coil.

The working principle is: $P1$ connects the flexible Rogowski coil and resistance $R1$, when meeting the conditions of $R1 >> R_t$, $R1 >> \omega L$ (R_t is inner resistance of coil, ω is upper-limit of operating frequency), the coil works as an exterior integrator. The coil induces by the measured current and output the differential signal of voltage that is proportional to the measured current, the differential signal of voltage is restored to the voltage signal proportional to the measured current through the integrator which consists of $R2$ 、 $C2$ 、 $U1$.

The lower limit of active integrator is determined by the constant of integral time: $f_L = \dfrac{1}{2\pi R_2 C_2}$; the upper limit is determined by the slew-rate of operational amplifier: $f_H = \dfrac{SR}{2\pi V_{om}}$, SR is slew-rate, V_{om} is the amplitude of output signal. The bandwidth of active integrator is: $BW = f_H - f_L$.

The performances of operational amplifier, integral resistance and integral capacitor could influence the actual performance of integrator. Especially the performances of operational amplifier and integral capacitor decide the bandwidth frequency of integrator. Integral capacitor needs the distributed inductance as small as possible, which can influence the bandwidth of upper limit frequency of integrator and cause the wave distortion. The capacity of integral capacitance and leakage resistance are chosen to be as big as possible without impacting the distributed inductance, which can reduce the impact of capacitor discharge on the precision. Operational amplifier is required of the following particular properties: high gain bandwidth, high slew-rate, high input-impedance, low bias current and low offset voltage, otherwise it can impact the bandwidth of upper limit frequency of integrator.

In order to validate the sample precision of this coil, the test platform is established shown in fig.7. The impulse lightning current generator generates 8/20μs and 10/350μs standard current waveforms with different amplitude and polarity. The standard current transducer and oscilloscope constitute the standard collection circuit. The collection device gets the precision of sample system by comparing the waveform of sample and standard circuit. The output current of impulse lightning current generator is preset in turn as: 1kA, 2kA, 10kA and 25kA, the positive impulse discharge test and the negative impulse discharge test are carried out each time, and then we can read the test data from the digital storage oscilloscope respectively.

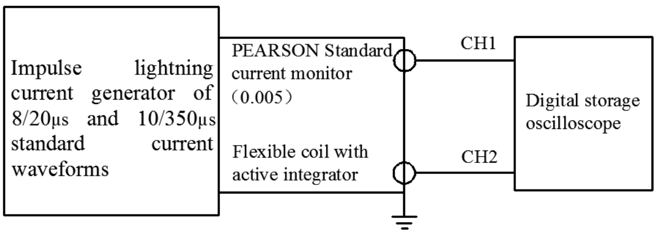


Fig.7 Wiring diagram of current monitoring

Using the test data to calculate the monitor error according to the following formula, the result needs to meet:

$$\delta = \left(\frac{|I_{m0} - I_{m1}|}{I_{m0}} \right) \times 100\%$$

In formula:

δ —— amplitude error;

I_{m0} —— amplitude reading of digital storage oscilloscope

I_{m1} —— amplitude of sample

The test results of 8/20μs waveform are shown in table2. The test results of 10/350μs waveform are shown in table3.

TABLE2 The testing results of 8/20μs waveform

Impulse current (8/20μs)	Standard current monitor (0.2kA/V) value(V)	Flexible coil with active integrator(V)	Monitoring error (%)
+1kA	+1.01	+1.018	0.79
+2kA	+1.97	+1.973	0.15
+10kA	+10.5	+10.446	0.51
+20kA	+20.3	+20.355	0.27
-1kA	-0.944	-0.934	1.06
-2kA	-1.86	-1.875	0.81
-10kA	-10.6	-10.554	0.43
-20kA	-20.3	-20.337	0.18

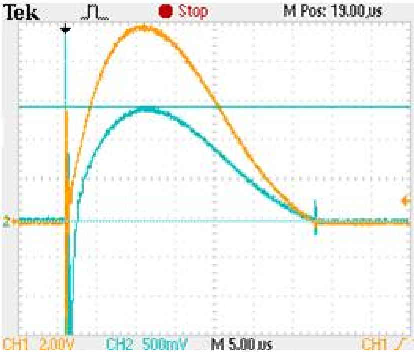
TABLE 3 The testing results of 10/350μs waveform

Impulse current (10/350μs)	Standard current monitor (0.5kA/V) Value(V)	Flexible coil with active integrator(V)	Monitoring error (%)
+1kA	+1.06	+1.08	1.89
+2kA	+2.08	+2.07	0.48
+10kA	+11.1	+11.122	0.20
+25kA	+25.2	+24.925	1.09
-1kA	-1.05	-1.048	0.19
-2kA	-2.02	-2.013	0.35
-10kA	-11.0	-10.745	2.32
-25kA	-25.2	-25.642	1.75

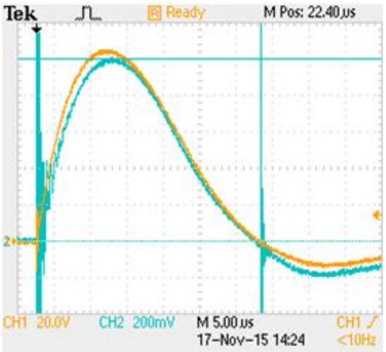
Fig 7 is a waveform diagram between the standard and the sample which are from impulse output current （8/20μs） preset as +1kA, +10kA, -2kA and -20kA.

Fig 8 is a waveform diagram between the standard and the sample which are from impulse output current （10/350μs） preset as +2kA、+25kA、-2kA、-10kA.

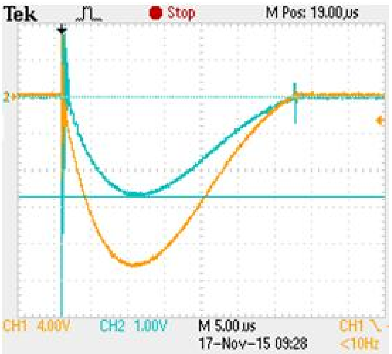
Waveform of +1kA:



Waveform of +10kA:



Waveform of -2kA:



Waveform of -20kA:

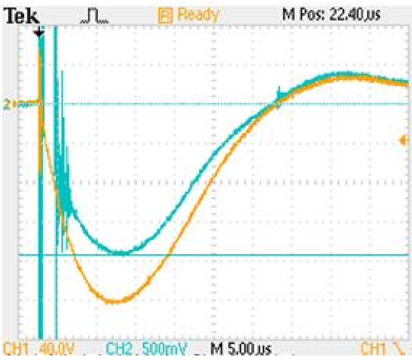
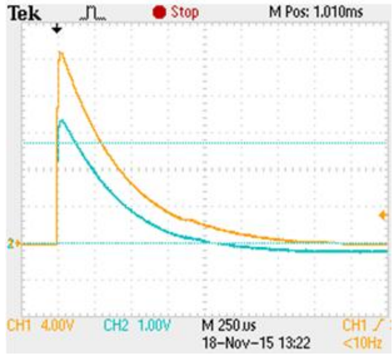
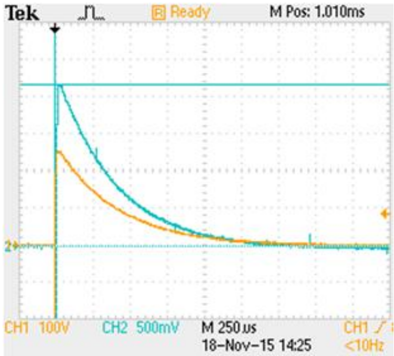


Fig 7 Standard waveform and sample waveform of current

Waveform of +2kA:



Waveform of +25kA:



Waveform of -1kA:

Waveform of -10kA:

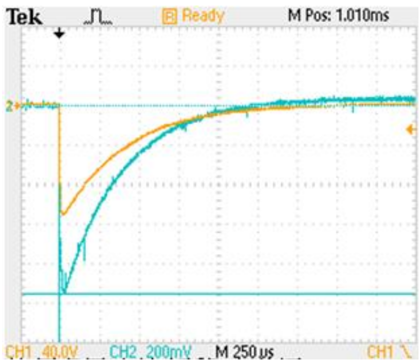


Fig 8 Standard waveform and sample waveform of current

V. CONCLUSION

A kind of flexible Rogowski coil with active integrator mentioned in this paper, realizes the lightning current collection of 8/20μs and 10/350μs with good linearity. It can collect the lower frequency signal of 10/350μs and higher frequency signal of 8/20μs with high precision. This kind of Rogowski coil resolves the problem of low precision of conventional Rogowski coil with passive integrator, expands the bandwidth, easy to install and provides good restoration of waveforms. But there is still much room for improvement. The circuit board is placed near the lightning cabling without any measures in electromagnetic shielding and electromagnetic compatibility (EMC), waveform burr is induced by high frequency noise of lightning. For example, the wave front of 8/20μs has many burrs due to the ring signal generated by the high-frequency component caused by the sharp variation of input signal, affecting the smoothness of waveform. This problem can be solved by designing a low pass filter in the future.

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