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CHARACTERISTICS ANALYSIS OF THE INDUCED OVERCURRENT GENERATED BY CLOSE TRIGGERED LIGHTNING ON THE OVERHEAD TRANSMISSION POWER LINE

YANG Shao-jie (杨少杰)[1], CHEN Shao-dong (陈绍东)[1], ZHANG Yi-jun (张义军)[2], DONG Wan-sheng (董万胜)[2], WANG Jian-guo (王建国)[3], ZHOU Mi (周 蜜)[3], WANG Xiao-bo (王孝波)[1], YU Hui (余 晖)[2]

(1. Lightning Protection Center of Guangdong Province, Guangzhou 510080 China; 2. Chinese Academy of Meteorological Sciences, Beijing 100081 China; 3. High Voltage and Insulation Research Institute of Wuhan University, Wuhan 430072 China)

Abstract: Techniques of artificially-triggered lightning have provided a significantly useful means to directly measure various physical parameters of lightning discharge and to conduct research on protection methods of lightning electromagnetic pulses. In this study, using capacitive and resistive dividers, current probes and optical fiber transmission devices, we measured and analyzed the induced overvoltage on the overhead transmission line and the overcurrent through Surge Protective Devices (SPD) when a lightning discharge was artificially triggered nearby on August 12, 2008 at Conghua Field Lightning Experiment Site. The triggered lightning discharge contained an initial current stage and eight return strokes whose peak currents ranged from 6.6kA to 26.4kA. We found that overcurrents through SPD were induced on the power line both during the initial continuous current stage and the return stroke processes. During the return strokes, the residual voltage and the current through the SPD lasted up to the ms (millisecond) range, and the overcurrents exhibited a mean waveform up to 22/69μs with a peak value of less than 2kA. Based on the observed data, simple calculations show that the corresponding single discharge energy was much greater than the values of the high voltage pulse generators commonly used in the experiments regulated for SPD. The SPD discharge current peak was not synchronous to that of the residual voltage with the former obviously lagging behind the latter. The SPD discharge current peak was well correlated with the triggered lightning current peak and the wave-front current gradient. The long duration of the SPD current is one of the major reasons why the SPD was damaged even with a big nominal discharge current.

Key words: triggered lightning; overhead transmission line; SPD; induced overcurrent

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1 INTRODUCTION

With respect to electric devices, power systems and communication systems, direct lightning strikes cause much more damage than lightning induction. For high-voltage power transmission lines of 110kV or above, direct lightning strikes, however, account for only 10% of the insulation breakdown accidents induced by lightning strikes, yet the same accidents caused by near lightning-induced overvoltage is over 90%. The fault trip rates of Dravtion and Mills power distribution networks are 55% and 29% respectively, 3/4 of which are caused by lightning induction [1]. Matsuo et al.[2] used electric geometric models and the Eriksson model to calculate the occurrence of overvoltage under direct lightning strikes and inductions. They found that the occurrence of induced overvoltage on power transmission lines goes higher as the voltage grade goes lower. More importantly, more electronic devices have been used on a massive scale for data collection, system control or communication, which generally have low signal voltages and are very sensitive to various electromagnetic disturbances. The electromagnetic radiation of lightning can disturb or damage electronic devices through various means, including coupling to power lines or signal lines, or direct coupling to electric or magnetic fields, or

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Biography: YANG Shao-jie, senior engineer, mainly undertaking the research on the protection of lightening.
E-mail for correspondence author: sjyang@grmc.gov.cn

electromagnetic radiation. Therefore, it is very meaningful to study the disturbance by electromagnetic induction of lightning.

The numerical approach to study the overvoltage on overhead power transmission lines caused by lightning can have two steps. First, calculate the electromagnetic field around the lightning channel by means of a mathematical model for lightning strokes. Second, build a mathematical model for coupling the electromagnetic field with the overhead transmission line and calculate the overcurrent on the overhead transmission line. Currently, in China and other countries, different methods have been developed to carry out many studies on the electromagnetic field around the lightning channel[3-5] and much work has been done with regard to the coupling model of electromagnetic fields and power transmission lines [6-9]. However, the information and data from real observations on induced overvoltage are much less, because of the instantaneity and huge destruction caused upon lightning occurrence.

As the rocket lightning technology keeps on developing, the artificial lightning-arresting technology provides an effective means to study the lightning protection for power systems and to acquire overvoltage information and data. In foreign countries, studies have been carried out on overvoltage caused by direct strike or induction of artificial lightning[10-12]. In China, much work has been done recently in experiments and theoretical analyses of induced overvoltage[13-15]. Mata and Rakov [16] reported on the capture of an artificial lightning as it directly stroke a low-voltage power transmission line and studied the diversion by SPD at different positions on the lead and the related current characteristics. DeCarlo et al.[17] investigated lightning currents directly transporting into a lightning protection system and studied the current distribution between the neutral line of a earthing system and the power cable of a residential building and the remote earthing connection. This paper uses a near artificial lightning on August 12, 2008. On the basis of the SPD residual voltage measurements of a low-voltage power supply system, the characteristics of induced overcurrent through the SPD are studied, in comparison with the current from direct lightning strikes and the waveform tested in a high-voltage lab. The main reasons why the overcurrent from a near lightning damaged the SPD are analyzed.

2 TEST LAYOUTS AND MEASURING INSTRUMENTS

In the summer of 2008, the overhead power transmission line at the artificial lightning experiment site was used to develop studies on protection of induced overvoltage and overcurrent. As shown in Fig. 1 below, the overhead power line passes through the household end and is then inserted into a tube and buried underground for 52 m to supply power to an automatic weather station (AWS). Supported by wooden poles, it consists of a live line and a neutral line and is about 1200 m away from the nearest electric transformer. The household end and the front end of the collector are each installed with a SPD with $U_p \leq 1.75$ kV and the nominal discharge current of 20 kA. As shown in Fig. 1, the arresting point was 20.5 m away from the collector horizontally and about 30 m away from the nearest overhead line.

To measure the overvoltage by coupling on the power line and the overcurrent through the SPD when the artificial lightning is triggered, the household end and the front end live line (Line L) of the collector each had an impact divider and a Rogowski coil (as shown in Fig. 1). The impact divider is a capacity-resistance type, which had one end connected with Line L and the other end earthed. The Rogowski coil is a core-through type, which measured the breakdown current of the SPD and has Line L run through its center. The voltage dividing ratios of the divider are 204.9:1 and 203:1. The band width of the Rogowski coil is 150 MHz. The data of induced voltages and currents are collected by the collector and then transferred, through an optical fiber, to a computer in the lightning arresting control room. To protect the collector system from being damaged if the induced overvoltage or overcurrent is too big, the signals are attenuated by 100 times and then collected and recorded by a high voltage insulated optical fiber data collection system, at a sampling rate of 5 M/s and a sampling length of 0.8 s. All the measuring instruments and systems have been tested and calibrated by the High Voltage and Insulation Technology Institute of Wuhan University on the site.

3 VOLT-AMPERE CHARACTERISTICS OF SPD

Figure 2a gives a curve of the volt-ampere characteristics of a normal SPD before the experiment. As shown, when the varistor is run through by a DC current of 1 mA, the voltage at either end of the SPD is about 640 V, which is the varistor voltage of the SPD. Also as shown, when the SPD is run through by a very weak current of tens of μA, there is an obvious sudden change of voltage at either end (when the current is 40 μA, the voltage at either end of the varistor is close to 500 V) and then the voltage increases slowly as the current increases. When the varistor is run through by a current of 1 mA or below, the SPD is not supposed to be in service in terms of engineering[18]. With the help of a varistor tester, it is further found that as the current through the varistor increases further, the voltage at either end of the varistor also increases. When the current reaches 20 mA, the voltage at either end of the varistor is about 710 V. This indicates that the clamping voltage of the varistor is not constant, but changes in a nonlinear form with increasing or decreasing current. That is, the internal resistance changes in a wide range. In addition, the volt-ampere characteristics of the varistor under a DC current are much different from those under an impact current, as the latter has a bigger operation voltage and residual voltage. Figure 2b contains the volt-ampere characteristics of the SPD which was damaged during the experiment with artificially triggered lightning. As shown, when the SPD is damaged, the zinc oxide resistor loses its characteristics to become a linear resistor.

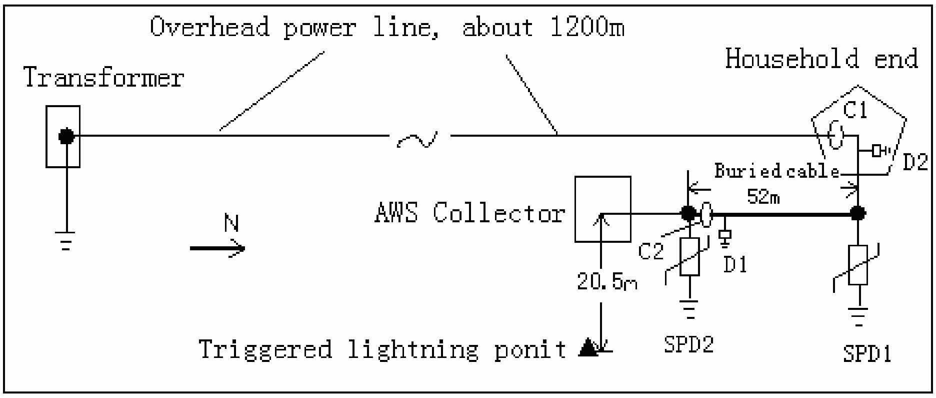

Fig.1 Test layout of induced overvoltage and overcurrent on the power line. (C1, C2 are Rogowski coils and D1, D2 are dividers.)

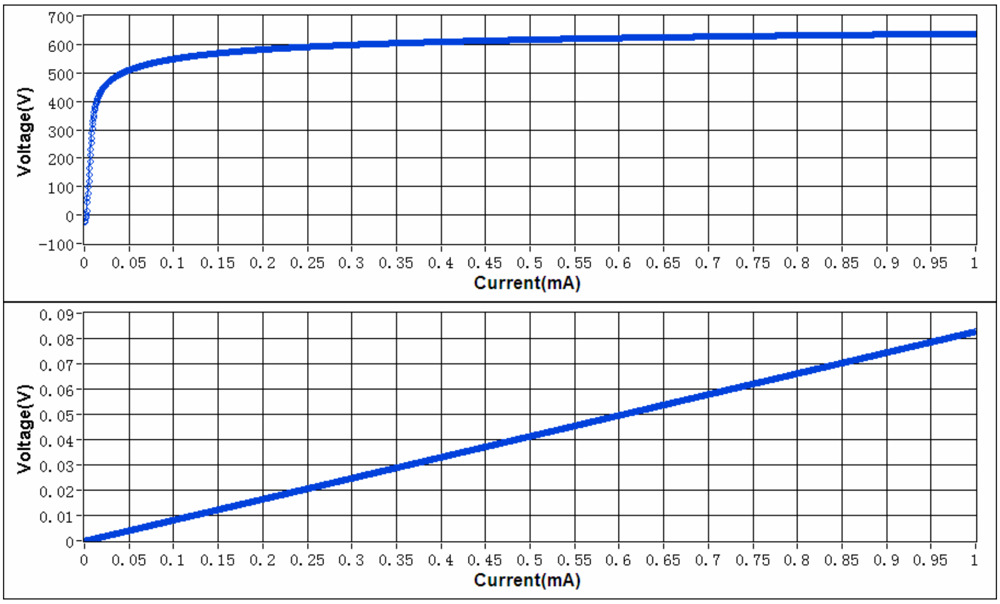

Fig.2 Volt-ampere characteristics of SPD. (upper panel: the SPD is normal before the experiment; lower panel: the SPD is damaged after the experiment)

4 OVERCURRENT CHARACTERISTICS OF SPD

During the lightning protection experiment on August 12, 2008, the SPD at the household end was disconnected and the SPD at the front end of the collector was in a normal working condition. At 17:09:21, the electrode successfully triggered a negative lightning (hereinafter referred to as F170921). When the induced overvoltage of line coupling was transmitted to the front end of the collector, the measuring system recorded the residual voltages and related overcurrents of this process. As evident from the recorded currents and the fast or slow electric field changes of the triggered lightning discharge, F170921 contained totally eight return strokes. The discharge process consisted of initial continuous currents and subsequent return strokes. With respect to the return strokes, the first biggest current was –26.4 kA (at the 8th return stroke), the second biggest current was –24.4 kA (at the 4th return stroke) and the smallest current was –6.6 kA (at the 1st return stroke). Because the induced overvoltage and overcurrent recording length is limited, the measuring system only recorded the induced overvoltages and overcurrents on the SPD at the initial stage of continuous current and the first seven return strokes. The waveform of the induced overcurrents is shown in Fig. 3.

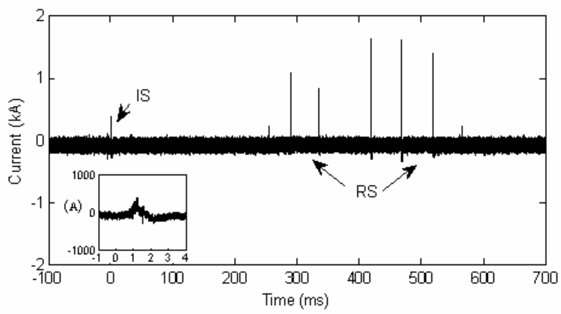

Fig.3 Waveform of SPD overcurrents measured at the frontend of an AWS collector.

4.1 *The induced overvoltages of SPD at the initial stage of continuous current*

Figure 3 presents the waveform of the overcurrents that ran through the SPD, as measured at the front end of the AWS collector, after F170921 was successfully triggered. The overcurrents can be divided into the initial stage (IS) and the return stage (RS). As shown in an enlarged view of the IS stage, with respect to the initial stage of continuous currents, the induced overcurrents are all below 1 kA, the maximum current being 470 A and the minimum current being about –220 A which lasts longer. Because of the noises of the measuring system (about –80 A on average), the IS is segmented at every 50 μs in order to calculate the average current of each segment (without noises). As shown in Fig. 4, the stage from 0 to 6 ms is divided into 120 segments. The initial current through the SPD starts off as weak bipolar wave, then is evidently positive at about 0.5 ms and quickly increases, with the biggest average positive current of 345 A at 1.25 ms. It starts to be negative at 2 ms and thereafter. The biggest average negative current is 110 A, which lasts about 4 ms before the current reduces to oscillate around zero.

4.2 *SPD overcurrents at return stage*

Figure 5 shows the main peak of the induced overcurrents on the SPD by F170921 return strokes. Thereafter, subsequent induced currents do exist, but are very weak. As shown, the main peaks of the overcurrents on the SPD are all below 2 kA, but in a range of 0.22 – 1.64 kA, during the seven return strokes. The amount of discharges of the SPD is in a range of 0.01 – 0.17 C, 0.08 C on average or 0.54 C in total, which is almost equal to the electricity neutralized by one return stroke of the triggered lightning. The computation finds that the half-peak width of the seven return strokes has a geometric mean of 63.3 μs and 10% – 90% of current peak rise time has a geometric mean of 15.6 μs, corresponding to a current gradient of 0.04 kA/μs or 1/1000 of the source current gradient of the triggered lightning. Also, as shown, as caused by induced voltages on the overhead line, the breakdown current of the SPD has a shorter rising edge but a longer lowering edge. For the seven return strokes, the currents at the wavefront period T1[19] are in a range of 14 – 48 μs or 22 μs on average and those at the wavetail time T2[19] are in a range of 29 – 96 μs or 69 μs on average. For the triggered lightning F170921, the average wavefront time and wavetail time are 0.5 μs and 29.5 μs respectively. The above analysis shows that the breakdown currents of the SPD caused by direct lightning strike are much different from those caused by lightning induction. The latter has a smaller peak, a smaller amount of discharge and a smaller current rising gradient. Compared with the impact waveform of 8/20 μs at the high voltage lab, the breakdown currents caused by lightning induction have an average waveform of 22/69 μs, with the lengths of time at the wave front and tail about three times as large as those at the high voltage lab. If these two waveforms are experimented to impact the SPD with the same current peak, the currents caused by lightning induction would discharge more electricity and energy to the earth and be more dangerous to the SPD.

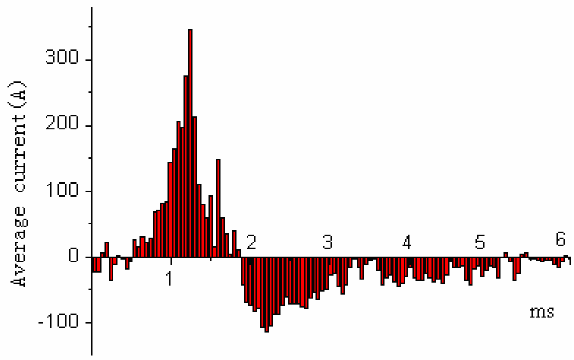

Fig.4 Waveform of average SPD overcurrent of 50 μs during the initial stage of F170921continuous current.

According to the nature of the SPD, when the current running through the SPD is 1 mA or above, the residual voltages at both ends of the zinc oxide resistor will be limited to a certain range. The main peak of the induced currents as analyzed above accounts for only a small part of the total continuation period of the residual voltages. Figure 6 shows that a majority of this continuation period sees weak subsequent currents discharge to the earth through the SPD. Figure 6 describes the residual voltages and overcurrent waveform on the SPD for the 2nd and 3rd return strokes of F170921. As can be shown in the figure, the continuation period of the residual voltages is in milliseconds, much longer than that in the high-voltage experiment[20]. The residual voltages for the seven return strokes are in a range of 0.6 – 8.1 ms or 3.1ms on average. Also as shown in the figure, for the 3rd return stroke, the residual voltage lasts 1.1 ms and lowers a little bit afterwards, and then after the current re-increases, the positive residual voltage is restored almost to the original value. When the current peak current is bigger, the subsequent current on the SPD fluctuates more obviously. However, as the measuring system contains many noises and the Rogowski coil is much erroneous in measuring certain low-frequency components, it becomes difficult to do a corresponding analysis between the characteristics of the subsequent current through the SPD and the residual voltage. This will be improved in later experiments.

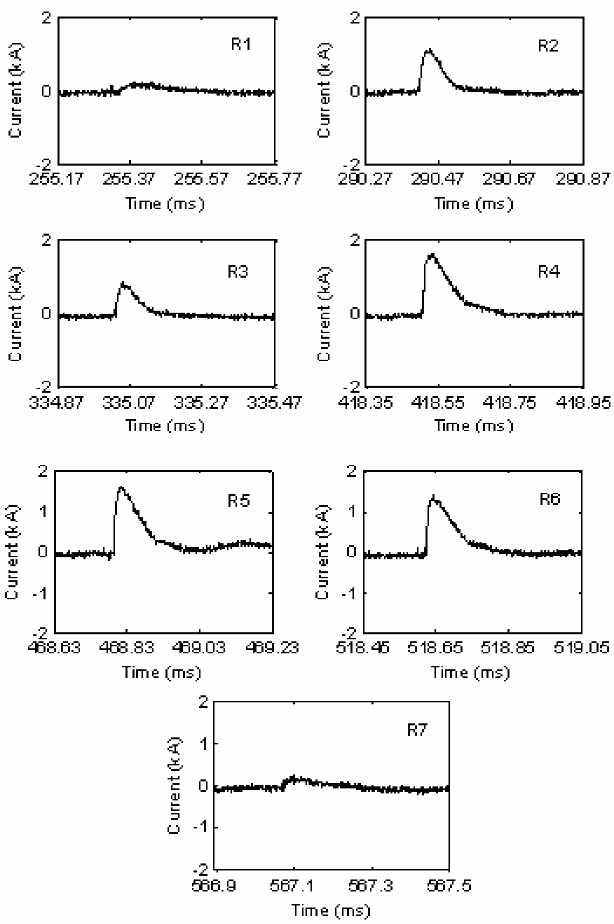

Fig.5 Waveforms of SPD induced currents during the return strokes of F170921. (R1 – R7: Return strokes 1 – 7)

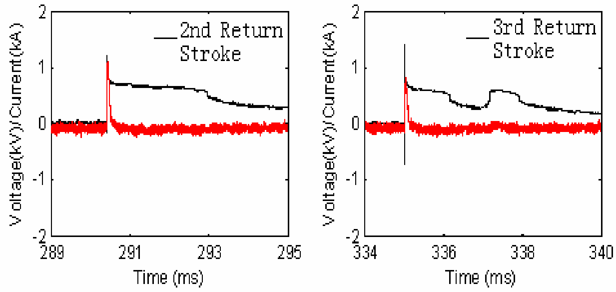

Fig.6 Waveforms of residual voltage and corresponding current of SPD at the frontend of the collector caused by returned, induced voltages of F170921. Thin black solid line: residual voltage; thick red solid line: induced current.

The through flow energy of the zinc oxide varistor is calculated using the following formula [21]: $W = \int_0^\infty u(t).i(t)dt$. On the basis of the residual voltage and current measurements, the through flow energy of the seven return strokes is in the range of 8.3 – 137.9 J or 64.6 J on average. This through flow energy is much higher than the through flow energy at one point of the high voltage experiment and the large energy is apparently caused by the longer duration of residual voltage and through current.

5 THE RELATIONSHIP BETWEEN INDUCED CURRENT AND INDUCED VOLTAGE OF RETURN STROKES

The correlation coefficient is 0.89 between the peak of the induced overcurrent of the SPD and the positive peak of the initial stage of the corresponding residual voltage, and is 0.92 between the former and the peak of the induced voltage at the household end. Compared with the residual voltage, the original induced voltage of line coupling is better correlated. Near the lightning strike, an induced voltage is produced on the low-voltage power line of the AWS. If the induced voltage is higher than the voltage of the zinc oxide varistor, the SPD will act to discharge the current. Because of the particularity, the varistor clamps the induced voltage by limiting the residual voltage to a certain range, and as the external induced voltage changes, the residual voltage changes by increasing or decreasing a little, but cannot fully reflect the characteristics of the induced voltage. Therefore, it is reasonable that the current through the SPD is less correlated with the peak of the residual voltage than the original induced voltage. Figure 7 is an enlarged view of the residual voltage and the SPD current waveform at the 5th return stroke of F170921. As shown, the induced overcurrent peak through the SPD is asynchronous to the residual current voltage, as the former obviously comes much later than the latter. the lag time of the seven return strokes is in a range of 17.8

- 62.6μs, 27.3 μs on average. The same phenomena exist in the high-voltage experiment [20].

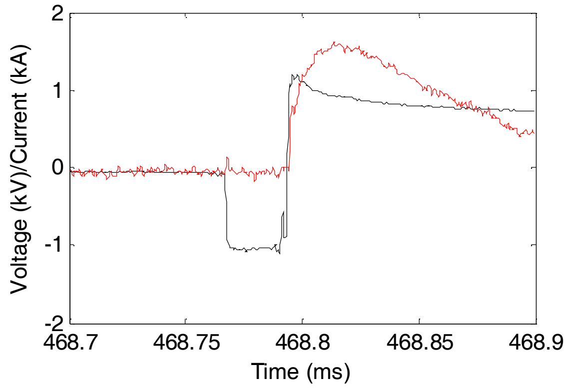

Fig.7 Enlarged view of waveforms of residual voltage and corresponding discharge current of the 5th return stroke of F170921(Thin black solid line: residual voltage; thin red solid line: induced current).

Moreover, the calculations show that the induced overcurrent peak through the SPD is also well correlated with the triggered lightning current peak and the wave-front current gradient, with correlation ratios of 0.97 and 0.89 respectively. The values for each return strokes are shown in Table 1.

Table 1 Lightning currents, gradients and overcurrents through SPD for the return strokes of F170921.

RS	SPD overcurrent peak (kA)	Lightning current peak (kA)	Lightning Current gradient (kA/μs)
1	0.22	6.6	17.05
2	1.10	18.2	56.99
3	0.83	12.9	31.09
4	1.64	24.4	54.48
5	1.62	24.2	51.19
6	1.40	20.3	41.95
7	0.22	10.8	22.26

6 CONCLUSIONS AND DISCUSSIONS

After analyzing the characteristics of the overvoltages on the near power lines and the breakdown currents of the SPD, as caused by an artificially triggered lightning, this paper concludes as follows:

(1) During the initial stage of continuous current and the return strokes, the triggered lightning induces obvious currents which have peaks of less than 2 kA, and the waveform during the return strokes is 22/69 μs on average.

(2) The continuation period of the residual voltages and the current through the SPD is in milliseconds. The residual voltages last about 3.1 ms on average and the single through flow energy is much bigger than that in the high-voltage impact experiment.

(3) The SPD discharge current peak is not synchronous to that of the residual voltage and the former obviously lags behind the latter. The SPD discharge current peak is well correlated with the triggered lightning current peak and the wavefront current gradient.

(4) The multiple impacts at short time intervals and long discharge duration of the return strokes are the main causes for the damage to the SPD during the experiment.

After the experiment with the triggered lightning F170921, it was found that the SPD of 20kA (nominal) at the front end of the AWS collector has been damaged, with obvious burns. From the volt-ampere characteristics curve in Fig. 2b, it can be found that the zinc oxide resistor has been damaged. From the waveforms of the residual voltages and induced currents of the first seven return strokes, it can be seen that the SPD was not damaged. The current (26.4kA) of the 8th return stroke was the strongest, but the residual voltage waveform was not recorded, it can only be deduced that the SPD was damaged by the 8th return stroke. The through flow energy of the SPD is the energy that the SPD absorbs to the maximum extent without damaging itself, which is also called the maximum bearable energy. If the energy to consume exceeds this through flow energy, the SPD will be damaged, such as flashover on the fringe, holing through, burning or explosion. The energy under the impact of lightning currents in a lab is an integral of power to time, which is difficult to calculate. Many manufacturers, which cannot provide the exact number, uses 8/20 μs impact current waveform crest to represent the nominal through flow energy for the purpose of convenience. On the basis of this definition, the varistor can bear multiple impact currents of 20 kA, but during the experiment, the maximum current through the SPD is less than 2 kA and the SPD was damaged by only one lightning. The causes are analyzed as follows: (1) the lightning current induced on the overhead line is not 8/20 μs, but is about 22/69 μs according to the above analysis. Under the same crest value, this current would discharge to the earth much more energy, easily damaging the SPD; (2) one lightning includes eight return strokes at intervals of tens to hundreds of milliseconds and the continuous impact in a short period of time can damage the SPD; and (3) the residual voltages of the return strokes continue in milliseconds (which was tens of microseconds during the experiment), and the maximum continuation is 8.1 ms. This indicates that there is a current of above mA or even A that runs through the SPD for a long period of time and causes the resistor card to heat up. It also produces in the power grid fluctuations a higher than nominal voltage and a power-frequency overvoltage for a short period of time. This overvoltage has a low crest, but lasts much longer than the transient overvoltage, which is unbearable to the SPD at the current manufacture level [22]. Therefore, this is the main cause of the SPD damage.

With respects to a natural lightning, the residual voltages lasts a much smaller duration, always in tens to hundreds of microseconds and the corresponding induced current peak is also much smaller, about hundreds of amperes. The SPD was working normally under several occurrences of natural lightning before the triggered lightning. On the basis of the above, it is easy to find that with regard to lightning strikes of tens of meters away from an overhead line, the induced currents are more dangerous because the induced voltage lasts a long period over the varistor voltage component, producing a long high current through the SPD. Coupled with multiple return strokes, this will easily damage the SPD. As the distance of lightning strikes enlarges to hundreds of meters, this potential damage will decrease substantially. The accident here tells that with regard to the protection of important overhead lines, multiple levels and types of protection means should be combined or the protection level should be heightened.

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