Coupling characteristics of lightning impulsive current on the underground coaxial cables

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Abstract. In this work, we analyzed the influence of lightning electromagnetic impulses on the underground coaxial cables through environmental simulation and got such conclusions. 1) The coupling voltage is proportional to the length of the underground coaxial cable. 2) The coupling voltage is inversely proportional to the depth of the underground coaxial cable. 3) The coupling voltage is proportional to the value of the impulsive voltage. These discoveries are of great application value for lightning protection techniques of coaxial cables.

1. Introduction
As a strong impulsive discharging phenomenon in nature, lightning is a major destructive and interruptive factor to electronic and information system in terms of its intense electromagnetic radiation effect. So IEEE listed it as a major public hazard in the information age. Lightning protection has been put more focus on nowadays. Electromagnetic shielding measures are implemented in the buildings and especially machine rooms. Inductive overvolatge caused by lightning could be introduced in through metal cables, damaging the interface modules of electronic devices, which is a vulnerable link of the lightning protection system. Coaxial cables are widely used in the information transmission, particularly in the high frequency telecom system. Lightning protection in this aspect is essential to the electronic system as a whole.

Overseas and domestic researchers have made some studies on the electromagnetic coupling mechanism of coaxial cables and twisted-pair cables by lightning. Li Xiangchao analyzed the impact of lightning impulses on twisted-pair cables and achieved the relationship between lightning interference and the cable length & height [1, 2, 3]. Xu Xiaopei studied the insertion resistance of aerial twisted-pair cables as well as the spectrum characteristics of coupling voltages [4]. Wang Hao discussed the impact of cable length, electric field polarization direction and terminal load on the cable responsive voltage [5]. Yang Chunshan etc. studied the coupling effect of the lightning electromagnetic impulse on the cables [6]. All these studies are based on theoretical calculation. Few studies have been carried out by experimental simulation in the lab. On top of that, most previous researches are focused on aerial cables, while nowadays there have been more underground ones to prevent lightning impulses in light of modern lightning protection theory.
2. Experimental scheme
An indoor metal rod was connected to the outdoor experimental device, as shown in Fig.1.

Cable length, underground depth and the impulsive voltage are the three variables. The cable length was 10m, 15m, 20m respectively. The underground depth is 10cm, 15cm, 30cm respectively. The impulsive voltage is 5kV, 10kV, 15kV, 20kV, 25kV, 30kV, 35kV, 40kV respectively. Discharge was triggered under circumstance of an optimal sphere gap. Then the coupling waves of the coaxial cable were displayed and saved. We repeated the experiment for three times to minimize the experimental error.

We used OriginProPorable to process the saved data and plot the wave line, spectrum graph and broken line graph to analyze the influence of each variable on the coupling effect.

3. Experimental data analysis

3.1. Coupling analysis of different cable lengths
Fig2(a) shows the wave of the cable 30cm underneath the ground with a voltage of 20kV, which is exactly the same with that is shown by the oscilloscope. It reaches a maximum value at the beginning of discharging, which means an ideal coupling effect. Then the coupling effect weakens as time going on. According to Fig.2(a), we could also come to the fact that the coupling spectrum is 0-5μs and that the peak voltage shows at 0.5μs. The coupling effect recedes quickly after 0.5μs. The lightning impulse could hardly be detected since 5μs. Coupling effect is relatively weak for the underground coaxial cable, we had to observe the peak voltage to compare the coupling effects in condition of different cable lengths. The result showed that a 20m cable had the best coupling effect, while a 10m one had the worst.

Fig 2(b) shows the spectrum of the cable 30cm underneath the ground with a voltage of 20kV. The oscillation spectrum of a coaxial cable is mainly between 0 and 5MHz. It had a maximum at the frequency of 0.5MHz approximately. Through observing the coupling effect in condition of the largest oscillation amplitude, we found that a 20m cable had the best coupling effect with the strongest electromagnetic wave, while a 10m cable had the weakest.

By comparison of Fig.2(a) and Fig.2(b), we came to a conclusion that for the cable 30cm underneath the ground with a voltage of 20kV, it had a best coupling effect when the length is 20m, and it had a weakest coupling effect when the length is 10m.
To further illustrate the influence of the cable length on the coupling effect, we then analyze the coupling effect of a cable 30cm underneath the ground with a voltage of 40kV.

Fig 2(c) shows the wave of the cable 30cm underneath the ground with a voltage of 40kV. The wave spectrum is mainly 0-5μs, and it has a maximum at 0.5μs. By comparing the line of a 20m cable (the top one), the line of a 15m cable (the middle one) and the line of a 10m cable (the bottom one), we came to the conclusion that a 20m cable has the best coupling effect, while a 10m cable had the weakest.

Fig 2(d) shows the spectrum of the cable 30cm underneath the ground. The oscillation spectrum in mainly between 0-5MHz, in which there are two major fluctuations. The first one was caused by a voltage impulse. By analysis we could see that the 20m cable had a larger vibration amplitude than the 15m and 10m one. Apparently, the 20m cable had the best coupling effect, and the 10m one had the weakest, with the 15m one having the medium. The second fluctuation didn’t conform to this rule, which was considered as an error caused by interference impulse, but not lightning.

Analysis of Fig. 2(c) and 2(d) showed a similar pattern in terms of the relationship of the cable length and the coupling effect.
In order to further illustrate the influence of the cable length on the coupling effect, we plotted the broken line chart of the voltage amplitudes versus different lengths of cables 30cm underneath the ground in Fig.3. The three lines in this figure all have a ascending trend, which shows that the coupling voltage are proportional to the impulsive voltage. By vertical analysis it is found that under circumstance of a fixed voltage, the line of the 20m cable is always on the top, with the 10m cable at the bottom and the 15m one in the middle. We could safely come to the conclusion that the 20m cable have the best coupling effect, and the 10m one have the weakest, which accords with the pattern discussed above.

We listed the data of Fig.4 in Table 1 to better compare the coupling effect of different underground cable depth.

| Impulsive voltage(kV) | 10m  | 15m  | 30m  |
|-----------------------|------|------|------|
| 10                    | --   | 0.10156 | 0.12442 |
| 15                    | 0.09715 | 0.13775 | 0.16442 |
| 20                    | 0.11911 | 0.15756 | 0.19909 |
| 25                    | 0.12285 | 0.15875 | 0.22575 |
| 30                    | 0.12784 | 0.18981 | 0.25775 |
| 35                    | 0.13624 | 0.19709 | 0.27909 |
| 40                    | 0.17903 | 0.22309 | 0.31642 |

3.2. Coupling analysis of different underground depths

Fig.4(a) shows the wave line of a 20m cable with a 20kV voltage. We could find some rules through comparison of the peak voltages, though the coupling effect is not that obvious for underground cables. The coupling wave is mainly between 0-5μs, and its effect faded out with time going on. The electromagnetic wave could hardly be detected after 5μs. The voltage peak occurred at around 0.5μs. At this point, the cable 10cm underneath the ground is on the top of the three lines, which means a best coupling effect. The cable 30cm underneath the ground is at the bottom, which means a weakest coupling effect.

Fig.4(b) shows the spectrum of a 20m cable with a 20kV voltage. In this figure, the coupling amplitude is mainly between 0-5MHz, in which there are three fluctuations. Two of them shows little patterns of the coupling effect. In the third one, we could see that the cable 10cm underneath the ground has a larger amplitude than the cable 20cm or 30cm underneath the ground. So the cable 10cm underneath the ground has the best coupling effect, while that 30cm underneath the ground has the weakest. By analysis of Fig.5(a) and Fig.5(b), we could come to the same conclusion.
Fig. 4(c) shows the wave line of a 20m cable with a 40kV voltage. The coupling wave is grouped mainly between 0-5μs, and its effect faded out with time going on. The electromagnetic wave could hardly be detected after 1μs. The voltage peak occurred at around 0.5μs. At this point, the cable 10cm underneath the ground is on the top of the three lines, which means a best coupling effect. The cable 30cm underneath the ground is at the bottom, which means a weakest coupling effect.

Fig. 4(d) shows the spectrum of a 20m cable with a 40kV voltage. In this figure, the coupling amplitude is mainly between 0-5MHz, in which there are three fluctuations. Two of them shows little patterns of the coupling effect. In the third one, we could see that the cable 10cm underneath the ground has a larger amplitude than the cable 20cm or 30cm underneath the ground. So the cable 10cm underneath the ground has the best coupling effect, while that 30cm underneath the ground has the weakest. By analysis of Fig.4(c) and Fig.4(d), we could come to the same conclusion.

Because of the relatively weak coupling effect of underground cables, we plotted a clearer broken line chart in Fig. 5. All the three lines had an ascending trend. We could also find that in condition of a fixed voltage value, the top line is that of the cable 10cm underneath the ground, and that the impulsive coupling voltage of the cable 30cm underneath the ground could hardly be detected. All these discoveries show that the cable 10cm underneath the ground has the best coupling effect, and the cable 30cm underneath the ground has the weakest. This is consistent with the pattern of the wave line and the spectrum chart.
We listed the data of Fig.5 in Table 2 to better compare the coupling effect of different underground depth for a 20m cable.

| Impulsive voltage(kV) | 10cm   | 20cm   | 30cm   |
|-----------------------|--------|--------|--------|
| 5                     | 0.11375| 0.10309| --     |
| 10                    | 0.19642| 0.16175| 0.12442|
| 15                    | 0.24975| 0.21775| 0.16442|
| 20                    | 0.29836| 0.26842| 0.19909|
| 25                    | 0.34717| 0.29242| 0.22575|
| 30                    | 0.38042| 0.29775| 0.25775|
| 35                    | 0.42575| 0.30648| 0.27909|
| 40                    | 0.50842| 0.34842| 0.31642|

3.3. coupling analysis of cables applied different voltages with fixed length and underground depth

Fig.6(a) shows the wave lines of a 20m cable 10cm underneath the ground applied a 20kV and 40kV voltage respectively. The wave is mainly grouped between 0-5μs, reaching the peak value at around 0.5μs. We could also see that the line of a 40kV voltage has a stronger fluctuation than that of a 20kV voltage, which means the former one has a better coupling effect.

Fig.6(b) shows the spectrum of a 20m cable 10cm underneath the ground applied a voltage of 20kV and 40kV respectively. From the graph, we can see that the frequency amplitudes are mainly between 0-5MHz and that the 40kV line is above the 20kV one. Apparently, the cable applied a 40kV voltage has a better coupling effect. By analysis of Fig.6(a) and Fig.6(b), we could come to the same conclusion.

Fig.6(c) shows the wave lines of a 20m cable 10cm underneath the ground applied a 20kV and 40kV voltage respectively. The wave is mainly grouped between 0-5μs, reaching the peak value at around 0.5μs. We could also see that the 40kV line is above the 20kV one, which means the former one has a better coupling effect.

Fig.6(d) shows the spectrum of a 20m cable 20cm underneath the ground applied a voltage of 20kV and 40kV respectively. From the graph, we can see that the frequency amplitudes are mainly between 0-5MHz and that the 40kV line is above the 20kV one. Apparently, the cable applied a 40kV voltage has a better coupling effect. By analysis of Fig.6(c) and Fig.6(d), we could come to the same conclusion.
We listed the data in Table 3 to better analyze the coupling effect of different voltages. By vertical comparison we found that the value of peak voltage was proportional to that of the impulsive voltage. This pattern conformed to what we got from the spectrum and wave lines above.

Table 3. Peak voltage coupling on the 20m cable 10cm and 20cm underneath the ground respectively

| Impulsive voltage(kV) | Coupling voltage(V) | 20m cable 10cm underneath the ground | 20m cable 20cm underneath the ground |
|-----------------------|---------------------|-------------------------------------|-------------------------------------|
| 5                     | 0.11375             | 0.10309                             |
| 10                    | 0.19642             | 0.16175                             |
| 15                    | 0.24975             | 0.21775                             |
| 20                    | 0.25836             | 0.26842                             |
| 25                    | 0.34717             | 0.29775                             |
| 30                    | 0.38042             | 0.29242                             |
| 35                    | 0.42575             | 0.30648                             |
| 40                    | 0.50842             | 0.34842                             |
4. Conclusion
In this paper, we plotted the wave lines and spectrum charts to analyze the coupling voltages and came to the conclusions as below.

1) The coupling voltage is proportional to the length of the underground coaxial cable. Experimental results showed that a 20m cable had the best coupling effect, with a 10m cable having the weakest. The peak value of the coupling voltage was larger in case of a longer cable.

2) The coupling voltage is inversely proportional to the depth of the underground coaxial cable. Experimental results showed that the cable 10cm underneath the ground had the best coupling effect, and that the cable 30cm underneath the ground had the weakest coupling effect. The peak value of the coupling voltage was smaller when the cable was laid deeper.

3) The coupling voltage is proportional to the value of the impulsive voltage. Experimental results showed that the cable applied a 40kV voltage had better coupling effect than that was applied a 20kV voltage.

4) The coupling voltage has a relationship with time. The wave was mainly clustered between 0-5μs, reaching its peak at around 0.5μs. After that, with time going on, the fluctuation weakened and disappeared eventually, and so did the coupling effect, which could also be shown in the spectrum chart.

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