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Lightning performance of EHV and UHV overhead transmission Lines in China southern power grid

Hansheng Cai, Lei Jia, Gang Liu, Shangmao Hu, Jian Shi
China Southern Power Grid Electric Power Research Institute, Guangzhou, China
liugang@csg.cn

Hengxin He, Xiangen Zhao, Junjia He
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China
Hengxin_He@hust.edu.cn

***Abstract*—Lightning stroke is the main cause of trip-outs of EHV and UHV transmission lines in China Southern Power Grid (CSG). In order to improving the lightning performance of overhead transmission lines, the lightning activities of CSG in 2006 to 2014 was analyzed. It indicates that the coastal Guangdong and Guangxi province are suffered more ground flashes, where the average ground flash density is over 7.98 flashes/km^2/year. 306 lightning flashover incidents of 500kV AC, ± 500kV HVDC and ± 800kV UHVDC transmission lines were investigated. It is inferred that about 84% lightning flashover incidents was caused by lightning shielding failure. The corresponding ground wire protection angle for 81% incidents is larger than 5°, and with protection angle decreases, lightning trip-out failures are significantly reduced. Based on the guidelines proposed by IEEE and CIGRE working group, CSG has developed their own lightning risk estimation tool named LPTL. The predication result of six 500kV AC transmission lines was compared to field experience which validates the IEEE recommended method for 500kV AC transmission lines. Further works should be done to revisit the validity of existing risk estimation method for HVDC transmission lines.**

Keywords-lightning perfromance; EHV; UHVDC; OHTLs; ground flash density; lightning flashover incidents; risk estimation tool; field experience

I. Introduction

Lightning stroke is the main cause of trip-outs of EHV (extra-high voltage) and UHV (ultra-high voltage) transmission lines [1]. Under the corporation of China Southern Grid (CSG), there are Yunnan, Guizhou, Guangdong, Guangxi and Hainan five province, are among them, Guangdong and Guangxi are the coastal energy load center, which suffer intense lightning activities. Yunnan and Guizhou are rich in hydropower resources while complex in topography and climate. Hydropower resources transportation in the west mainly rely on the 500kV AC, ± 500kV HVDC and ± 800kV UHVDC transmission lines to the coastal industrial zone. Compared with northern China, UHV and EHV transmission lines of CSG suffered a higher risk of lightning strike, therefore, it is a great challenge to effectively carry out lightning protection and ensure the security of power grid.

In the past half century, the lightning protection of transmission lines has made great progress. The invention of the lightning location system which pioneered by the United States [2], makes it possible to master the distribution characteristics of ground flash density on the macro. The observation on the lightning shielding failure images and current waveform of the UHV double-circuit transmission lines by Japanese researchers [3], lays a foundation for the improvement of lightning shielding failure analysis method including the electrical geometry model [4] (EGM) and the leader development model [5] (LPM). Many researchers dedicated to study the transient overvoltage caused by lightning strike by updating EMTP model [6] and FDTD method [7]. Lightning protection guidelines have been proposed by IEEE, IEC and GIGRE working groups, which also developed FLASH and other analysis software tools. Lightning protection measures such as reducing the protection angle, parallel gap and installing line arrester have been put into practical engineering applications. However, considering the situation of lightning activities and topography of CSG to evaluate line lightning fault risk, then analyzing and comparing the lightning protection operation experience of transmission lines to verify the lightning protection effect, these works still have an important reference value for improving the existing lightning protection technology system of transmission lines.

In this paper, the lightning activities of CSG during 2006-2014 were analyzed, and the lightning protection operation experience of total 63 EHV and UHV transmission lines were investigated. The CSG lightning protection performance analysis software named LPTL is developed and used to evaluate the lightning failure risk of these transmission lines. Finally, through the comparison of field experience and calculation analysis, the main causes and further works concerning lightning protection of transmission lines are put forward.

II. Lightning Activities of CSG

A. Lightning Location System in CSG

Development and application of lightning location system in CSG began in 1998. It mainly used the very low frequency ground flash electromagnetic wave band combined time-ofarrival (TOA) and magnetic direction finding (MDF) positioning methods which are similar to the lightning location system of the United States National Lightning Detection Network (NLDN) and the Japanese power company. At present, CSG lightning location system consists of 113 stations, 2 data centers, as shown in Fig.1. As the central and western regions of CSG are mountainous areas, in order to reduce the impact of the terrain on the detection efficiency, the number of stations in CSG is more than the Japanese lightning location system.

Chen [8] and other researchers assessed the performance indicators of the Guangdong power grid lightning flash detection network by the observation data from experiment of artificially triggered lightning and high building lightning strike observation. The research results show that the detection efficiency is about 94% and the average location error is 710m. According to the21 artificial triggering lightning samples, it can be known that the average error of the lightning current detection is less than 20%.

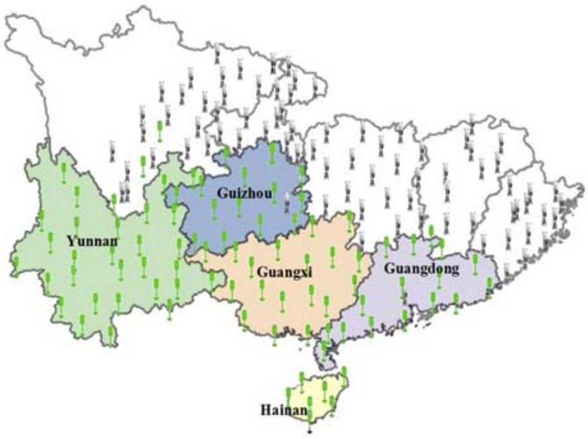


Figure 1. Layout of lightning location system in CSG (Only the green ones belong to the CSG).

On the one hand, the lightning location system of CSG is used to detect and accumulate ground lightning flash activities data, analyze and plot the ground lightning flash density distribution of CSG, and provide basic data for the lightning performance evaluation of transmission lines. On the other hand, according to the lightning trip time of transmission lines, the corresponding lightning current amplitude can be determined by the lightning location system, combined with the theoretical model calculation (EGM or EMTP), it can be determined that the trip is caused by lightning shielding failure or back flashover.

B. Ground Flash Data in 2006-2014

Lightning protection of transmission lines is mainly concerned with ground flash density and lightning current amplitude probability density distribution. In 2006-2014, CSG recorded a total of 59749099 times ground flash, its annual distribution is shown in Fig. 2. According to the observation, in the last five years, the lightning flash activities of CSG has been increasing year by year, which is most intense in 2009. Fig. 3 shows the monthly distribution of ground lightning activities in CSG in recent five years, it can be seen that lightning activities are mainly concentrated in summer (3-9 months), and winter lightning activities in CSG are weak.

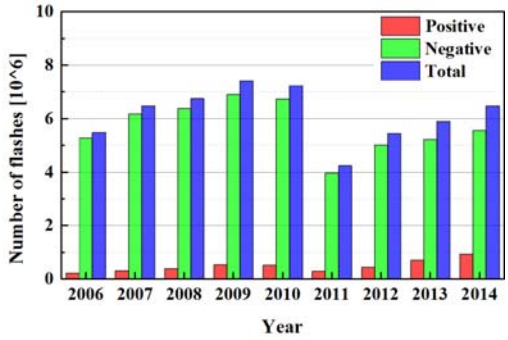


Figure 2. Annual distribution of ground lightning in CSG during the year 2006 to 2014.

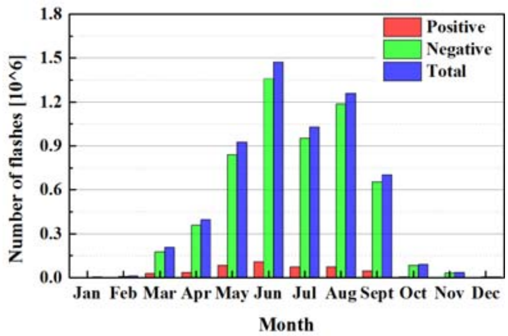


Figure 3. Monthly distribution of ground lightning in CSG during the year 2006 to 2014.

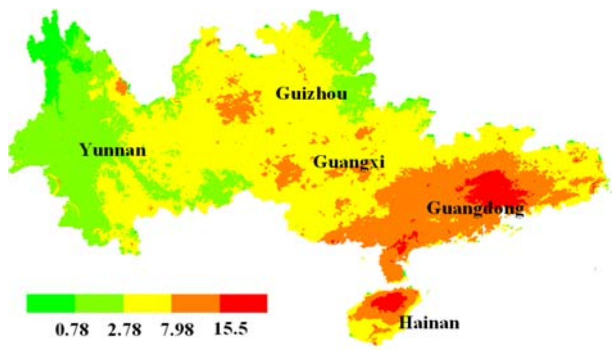


Figure 4. Statistical ground flash density in CSG during the year 2006 to 2014.

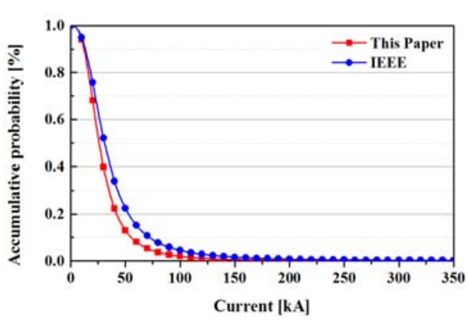


Figure 5. Accumulative probability of the lightning current.

In this paper, the grid method is used to draw the distribution map of ground flash density in CSG with the uniform grid sizes of 3km in both x and y directions, and the sample is the lightning location data in 2006-2014. The average ground flash density distribution of CSG in recent five years is plotted in Fig.4. According to the results, it is known that the activities are mainly concentrated in the Guangdong coast, central Guangxi and the northern mountainous areas of Guizhou. As a load center, the average ground flash density over 7.98 flashes/km^2/year in the Guangdong coast, it is a serious threat to the safety of the terminal transmission lines. For most mountainous areas in Guangxi and Guizhou, the

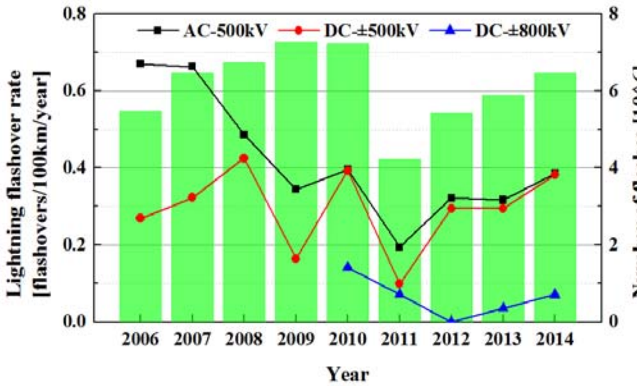


Figure 6. Annual distribution of the lightning flashover rate of EHV and UHV transmission lines in CSG.

average ground flash density is between 2.78 to7.98 flashes/km^2/year. Taking into account the role of the terrain, lightning protection of transmission lines in these areas is even more difficult.

In Fig. 5, the cumulative probability curve of lightning current amplitude is given by the data analysis of the lightning location system. Statistical results show that the median current is about 26kA, slightly less than 31kA, which is recommended by IEEE order. Although the average error of lightning current amplitude is about 20%, the curve in Fig.5 is obtained from 59749099 samples in 9 years, so it still has a certain guiding role to the lightning protection of actual lines.

III. Lightning Incidents of EHV and UHV OHTLs of CSG

In this paper, fifty-six 500kV AC transmission lines, five ±500kV DC transmission lines and two ±800kV UHV DC transmission line in CSG are treated as the investigation samples. From 2006 to 2014, Three hundred and six lightning flashover incidents in all are investigated and analyzed. The statistical sample reaches about 92147km·year, including 53498km·year 500kV AC transmission lines, 9886km·year ±500kV HVDC transmission lines and 1100km·year ±800kV UHVDC transmission lines.

The distribution of lightning flashover rate of China Southern Power Grid EHV and UHV AC or DC transmission lines is shown in Fig.7. Field experiences shown that the average lightning flashover rate of ±500kV DC transmission lines is lower than 500kV AC transmission lines. Despite the use of a negative protection angle, the lightning flashover rate of ±800kV UHV DC transmission lines is more than 0.1 flashes per 100km per year. In general, the lightning flashover rate of transmission lines is positively correlated with ground flash frequency, and the correlation coefficient is 0.8. About ninety percent of the lightning flashover events occurred in months from April to October and it's consistent with the monthly distribution of CG lightning flashes. However, the ground flash density is relatively high in 2009, the lightning flashover rate is not high, so it shows that the lightning flashover rate risk is also related with other factors such as terrain, etc.

In 306 lightning strikes flashover incidents, there are 293 flashover events was recorded by lightning location system, the detection efficiency is 96%. Distribution of lightning current amplitude of the 293 flashover events is shown in Fig.7. For 500kV AC transmission lines, there are 217 flashover incidents (10 flashover incidents are missed), about 69% of lightning current amplitude which causes trip-out failures is between 30kA to 50kA. For ±500kV HVDC transmission lines, there are 83 flashover incidents (3 flashover incidents are missed), 87% of lightning current amplitude which causes trip-out failures is under 50kA. Among of them, there are 69 lightning flashover events occur on positive pole for the bipolar operation situation. There are 6 trip-out incidents for ±800kV UHV DC transmission lines. The corresponding lightning current amplitude is less than 50kA, among which three times occur on the positive pole and two times occur on negative pole.

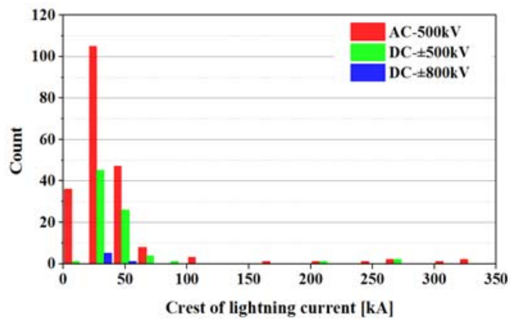


Figure 7. Histogram for crest of lightning current measured by lightning location system which caused lightning flashover of the transmission lines in CSG during the year 2006 to 2014.

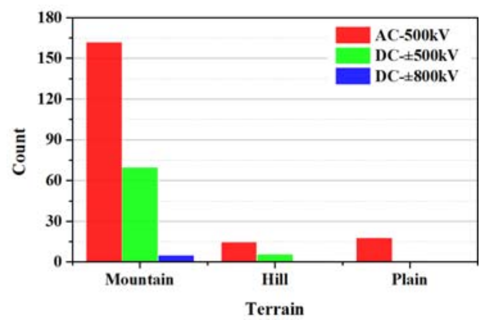


Figure 8. Topography statistics of lightning shielding failure in CSG during the year 2006 to 2014

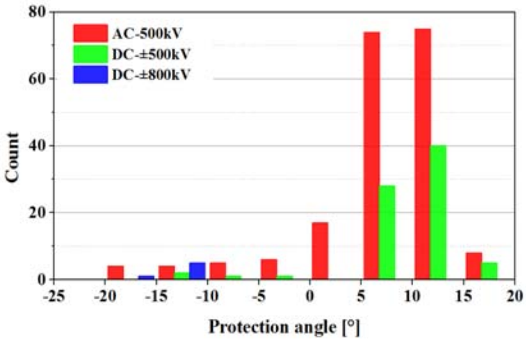


Figure 9. Protection angles statistics of lightning shielding failure in CSG during the year 2006 to 2014

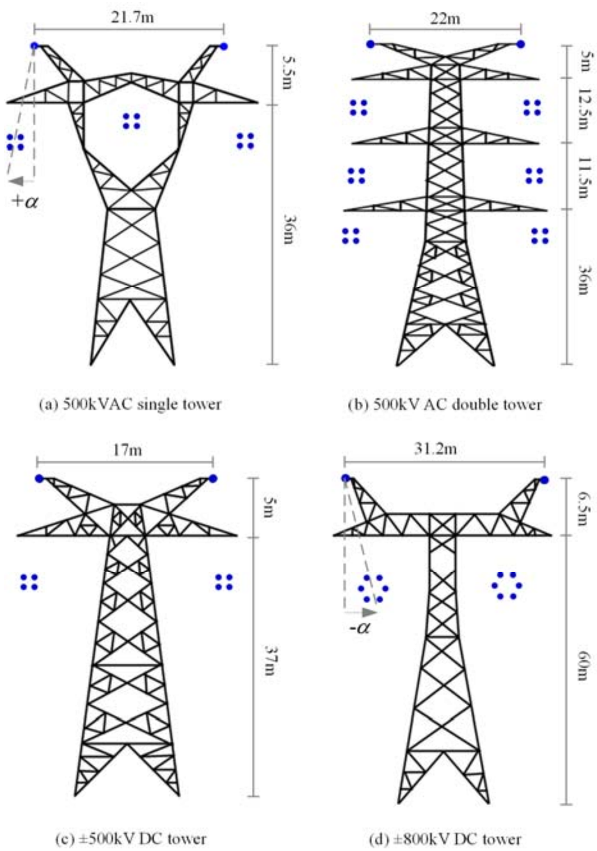


Figure 10. Tower layout in Figure 9

Lightning shielding performance of transmission lines is closely related to topography and line structure. Topography is divided into three kinds, including: plain, hill and mountain area in the actual survey. The relationship between topography feature and lightning flashover incidents occurred is shown in Fig.8. Statistical results show that over 90% of the lightning incidents occurred in mountain area for 500kV AC, ±500kV HVDC and ±800kV UHVDC transmission lines, respectively.

In this paper, the relationship between lightning flashover incidents and the protection angle of specific transmission line is also discussed. The actual ground wire protection angle considering sag for the line span where lightning shielding failure occurred were derived and shown in Fig. 9. Statistical results indicated that for 500kV AC and ± 500kV HVDC transmission lines, the corresponding ground wire protection angle for 81% of lightning trip faults is larger than 5°, and with protection angle decreases, lightning trip out failures are significantly reduced. For ±800kV UHVDC transmission lines, lightning flashover faults still occurred even though the negative protection angle was adopted. It might be related to the effect of the DC operating voltage, corona space charge or topography.

IV. Lightning Risk Estimation of EHV and UHV OHTLs

A. *Lightning Risk Estimation Tool*

According to the discussion of previous parts, it could be revealed that the lightning flashover risk of OHTLs not only depends on the ground flash activity frequency, but was also closely related to the line configuration, local topography feature, etc. Therefore, in order to conduct a credible lightning risk estimation, it is crucial to take into account of those risk factors. On the other hand, it is of great value to improve lightning risk estimation method by comparing the predicted lightning failure risk and field experience for years.

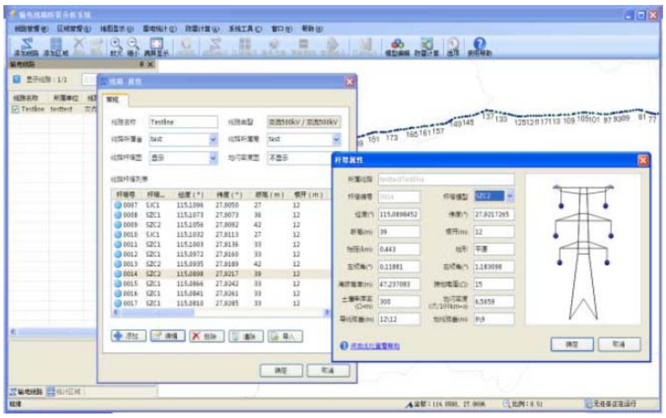


Figure 11. Illustration of LPTL's graphic user interface.

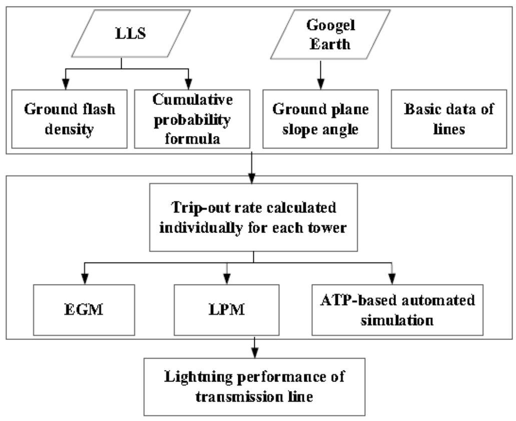


Figure 12. Schematic diagram of lightning performance assessment for overhead transmission lines.

Based on the guidelines proposed by IEEE and CIGRE working group [9, 10], CSG has developed their own lightning risk estimation method. A software named lightning protection analysis tool for OHTLs (LPTL) has been developed by a joint group from CSG and HUST shown in Fig.11. Fig.12 shows the implementation procedure of the assessment method for lightning performance of overhead transmission lines.

Lightning performance assessment of transmission line can be divided into two parts: fundamental data statistics and trip-out rate calculation. A grid statistical method is carried out to obtain ground flash density and cumulative probability function of the lightning crest current with the lightning data in long term detected by lightning location system (LLS) by developing a data interface between the tool and LLS. Using the GOOGLE EARTH API interface, the slope angle of ground plane at specific tower could be derived. In order to input and management of the line configuration data, a software module named tower template editor has been carried out, which could describe the geometric dimensioning of each tower, configuration of insulator string, footing impedance, etc.

For the outage rate calculation, the EGM and LPM were integrated in this tool for shielding failure analysis. According to electro-geometric models, the striking distance to conductor S could be expressed by the following equation with the lightning crest current as a parameter and can be associated to striking distance to earth surface D by using a factor γ as (1):

$$S = A \cdot I^{B} = \gamma \cdot D \tag{1}$$

where I is lightning crest current (kA) and S, D are in meters. The value of A, B and γ for striking distance proposed by different researchers have been integrated in LPTL. A two dimensional leader progression model was provided in LPTL, which mainly based on the conception proposed by Dellerra [11] and Rizk [12]. The detail of LPM method can be acquired elsewhere [13]. LTPL provides an interface to EMTP for Back-flashover calculation. An automatic simulation method for back-flashover rate of transmission line has been proposed. It could create an EMTP script file according to fundamental data of OHTLs, which could describe the basic circuit element to calculate lightning surge phenomenon, including: lightning current and impedance, tower equivalent model, tower footing impedance, insulator string flashover, transmission line, induced voltage, AC sources and matching termination.

B. Comparing with Field Experience

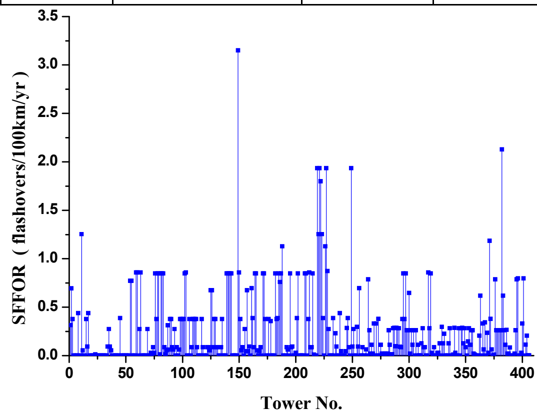
LPTL have been used to estimate the lightning risk distribution along the line corridor. The prediction result could provide reference for the lightning protection updating of specific overhead transmission line.

In order to analyze the validity of LPTL, the prediction results were compared to the field experience. In this preliminary work, there are six 500kV AC transmission lines with integrity data are analyzed. The ground flash density along line corridor was derived from Fig. 4. The slop angle at each tower could be calculated by the longitude, latitude and elevation data. The lightning shielding failure flashover rate (SFFOR) was calculated by IEEE proposed EGM. The back-flashover rate (BFR) was calculated by EMTP. Fig. 13 shows the SFFOR and BFR distribution for each span of transmission line num. 5. The average lightning flashover rate could be yielded by the weighted average strategy. The estimated average lightning flashover rate and field operation data were summarized in Table I. It should be noted that the SFFOR values are higher than BFR values. The reason may be that the transmission lines in Table I are mostly located in mountain areas, and the insulation level of these transmission lines are very high.

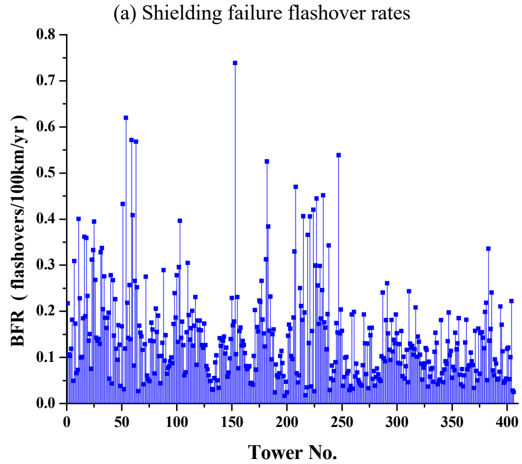
Comparative analysis between simulation results and observed results finds little discrepancy. It indicates that the IEEE method considering practical condition of transmission line is credible to estimate the lightning performance of 500kV AC transmission lines in southern China.

TABLE I. THE ESTIMATED AVERAGE LIGHTNING FLASHOVER RATE AND FIELD OPERATION DATA

No.	SFFOR (flashovers/100km/yr)		BFR (flashovers/100km/yr)	
	LPTL	Field experience	LPTL	Field experience
1	1.19	1.22	0.16	0
2	0.63	0.42	0.15	0
3	1.17	1.21	0.18	0
4	0.42	0.66	0.16	0
5	0.27	0.37	0.15	0.18
6	0.64	0.46	0.12	0



(a) Shielding failure flashover rates



(b) Back-flashover rates

Figure 13. Distribution of lightning performance for transmission line num. 5

The result shows that SFFOR of six OHTLs is larger than BFR, and that is consistent with operation experience of 500 kV AC transmission lines. Further works should be carried out in the following two aspects. The first one is going to do more comparison works between field experience and computation results for 500kV AC transmission lines. The computation parameters of EGM method and lightning surge analysis model could been revised to get a more credible predication. The second aspect is to revisit the validity of existing risk estimation method for HVDC transmission lines. It should be paid attention to seek lightning shielding failure flashover mechanism of for ±800kV UHVDC transmission lines.

V. CONCLUSION

Lightning performance of EHV and UHV transmission lines in China Southern Power Grid were presented. Three aspects work have been done. Firstly, the lightning activities of CSG in 2006 to 2014 was analyzed. Secondly, the lightning flashover incidents of 500kV AC, ± 500kV HVDC and ± 800kV UHVDC transmission lines were investigated. Finally, the lightning risk estimation tool have been developed and compared to the field experiences. It could be summarized as follows:

- It indicates that the coastal Guangdong and Guangxi province are suffered more ground flashes, where the average ground flash density is over 7.98 flashes/km^2/year. For most mountainous areas in Guangxi and Guizhou, the average ground flash density is between 2.78 to7.98 flashes/km^2/year.
- 306 lightning flashover incidents of 500kV AC, ± 500kV HVDC and ± 800kV UHVDC transmission lines were investigated. It is inferred that about 84% lightning flashover incidents was caused by lightning shielding failure. The corresponding ground wire protection angle for 81% incidents is larger than 5°, and with protection angle decreases, lightning trip-out failures are significantly reduced.
- Based on the guidelines proposed by IEEE and CIGRE working group, CSG has developed their own lightning risk estimation tool named LPTL. The predication result of six 500kV AC transmission lines was compared to field experience which validates the IEEE recommended method for 500kV AC transmission lines. Further works should be done to revisit the validity of existing risk estimation method for HVDC transmission lines.

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