International Conference of Electrical, Automation and Mechanical Engineering (EAME 2015)

# Analysis on the Technology and Economy of Lightning Protection Measures for Treble-circuit Transmission Lines

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***Abstract*—The treble-circuit transmission lines are widely used to increasing energy transportation efficiency and saving land. Because of symmetrical electric structure, the treble-circuit transmission lines suffer from lightning trip-out for more than one circuit in a lightning strike. In this paper, an analysis model for lightning performances of treble-circuit transmission line was established. A typical treble-circuit transmission line with abundant operating data was taken as analytic target. The technical economies of two lightning protection devices and four layout schemes were discussed. By setting insulator parallel gaps and surge arresters in one circuit of a treble-circuit transmission line to break the electric balance, the average lightning trip-out rate for more than one circuit flashing can be reduced by 50%. According to the analysis result of lightning performance, setting lightning protection devices selectively can improve its lightning performance effectively with lesser cost, which has a good technology and economy.**

***Keywords-lightning protection; treble-circuit transmission line; technology and economy; measure; back striking trip-out***

## I. INTRODUCTION

As the ever-increasing requirement for power energy and reducing of land source, more and more multi-circuit transmission lines are planned and established. By now, in the developed area in the east of China, more than 87% of transmission lines were built with the double-circuit or multi-circuit forms.

Double-circuit or multi-circuit transmission lines usually have higher towers comparing with single-circuit transmission lines. Therefore, they are stroke by cloud-ground flashes more frequently, and their lightning withstand levels of back striking (LWLBS) are lower. Moreover, since the symmetry of multi-circuit transmission line, the lightning back striking usually cause trip-out in more than one circuits. According to the operation record, only in Guangzhou gird in China, during the 2003 to 2011, 41 trip-outs in both circuits caused by lightning striking happened. Lots of researches on the lightning performances of double-circuit transmission line had been carried out [1-4]. The constructions of treble-circuit transmission lines are more complex, but few relative researches are proposed.

In order to propose a lightning protection measure with well technology and economy for treble-circuit transmission line, the performances and costs of several lightning protection measures for treble-circuit transmission line were studies. Firstly, the basic information of a typical treble-circuit transmission line was laid out, such as the tower structure, the distribution of ground flash density, the ground resistance of each tower. Then the calculation model for LWLBS of towers in EMTP was introduced. Thirdly, the present lightning performance of this transmission line was estimated. Finally, the performances and costs of four lightning protection measures for this transmission line were compared, and suggestions were summarized and proposed.

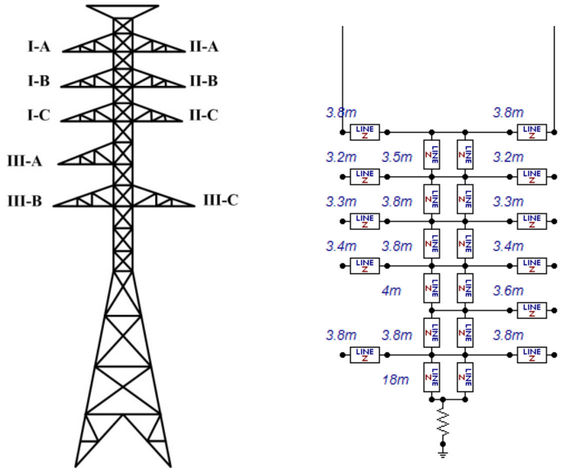
## II. ANALYSIS OBJECT AND ANALYSIS MODEL

### *A. Basic Data of a Typical Treble-circuit Transmission Line*

The typical treble-circuit transmission line is the 110 kV Kong-Fu transmission line, which belongs to the south grid of China. Its length is about 15.9 km, and it has 50 towers. The arrangement of phase conductors of three circuits is shown in Fig.1 (a). The I-circuit was set on the left of the top floor, while the II-circuit was set on the right of the top floor. And the III-circuit was set on the bottom floor with a triangular type. The tower head constructions are not much different between towers, and the heights of the bottom cross arm (HBCA) change from 18.5 m to 60.3 m. Two kinds of insulators were applied in this transmission line, i.e. the glass insulator and the composite insulator. The dry arcing distance is 1.0 m and 1.168 m for the glass insulators and the composite insulators respectively. The insulator form in a tower is the same. 20 towers are with glass insulators, and the rest of these towers are with composite insulators. The ground resistances of each tower are shown in Fig.2. Most tower ground resistances are between 4 Ω to 8 Ω.

The Kong-Fu transmission line is covered by the lightning location system (LLS). Therefore, the ground flash density for each segment of the transmission line can be calculated from monitoring data of LLS from Aug. 1$^{st}$ 2013 to Aug. 1$^{st}$ 2014, and the ground flash density distribution is shown in Fig.3. During this period, the transmission line was stroke 12 times, and these lightning strikes cause 22 trip-outs. 18 trip-outs are with double circuit or treble-circuit. And the lightning trip-out rate with double circuit or treble-circuit is about 75 /100km·a, which is fairly high.




(a) Tower structure (b) Tower model in EMTP

FIGURE I. ARRANGEMENT OF PHASE CONDUCTORS OF THREE CIRCUITS.

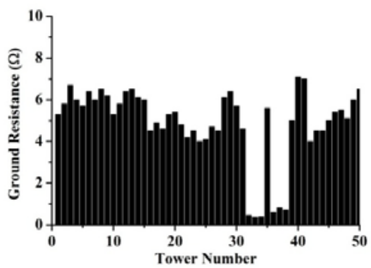



FIGURE II. TOWER GROUND RESISTANCES.

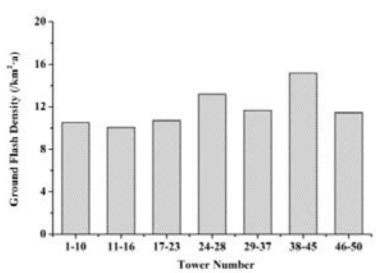



FIGURE III. DISTRIBUTION OF GROUND FLASH DENSITY.

### *B. Analysis Model*

*1) Tower and transmission line model:* In order to estimate the lightning trip-out rate without or with lightning protection measures, the LWLBS calculation model was built in EMTP. It primarily contains the tower model, the insulator flashover model and the transmission line model.

There are three main tower models, i.e. the lumped parameter model, single wave impedance model and multi-wave impedance model. In which, multi-wave impedance model is the most sophisticated, particularly to high and complex towers. In this paper, the multi-wave impedance model proposed by T. Hara is used to model towers [5, 6]. The multi-wave impedance model of tower in Fig. 1(a) is shown in Fig. 1(b).

Transmission line model includes lumped parameter model, Bergeron model and frequency domain model. Due to the extremely high amplitude (kA) and frequency (μs) of the lightning current, when the lightning current traveling into the transmission line, the line electrical parameters subsequently change, the effect of the inductance and capacitance become significant. In the frequency domain model of transmission line, the line electrical parameters relating to the frequency are applicable for the magnetic transient analysis in transmission line of high frequency response. Above all, the frequency domain model is suitable for the transmission line model, corresponding to the JMarti model in EMTP.

*2) Insulator flashover model:* The Insulator flashover model calculates the insulator flashover time based on the voltage applied to insulators. There are three kinds of models, i.e. the definition method (DM), the intersection method (IM) and the leader propagation method (LPM). The LPM bases on the air gap discharge theory. Therefore it is sophisticated and has an excellent adaptability. According to the air gap discharge theory[7], for the streamer developing, the background electric field $E_{cri}$ maintaining the development of streamer should be about 500 kV/m, and the development of leader need sufficient charges supplied by streamer. Considering the leader channel as a good conductor, the voltage between the two poles of insulator is applied to the residual air gap between the leader tip and the cathode. The leader developing velocity is related to the electric field in the residual air gap, which can be indicated as[8]:

$$v_L = \frac{dL(t)}{dt} = kU(t)\left[\frac{U(t)}{D-L(t)} - E_{cri}\right] \quad (1)$$

where $L(t)$ is the length of leader development, m; $U(t)$ is the voltage applied to the insulator, kV; $D$ is the length of insulator gap, m; $E_{cri}$ is the leader inception electric field, kV/m; $k$ is experimental coefficient relating to the insulator category and voltage polarity applied, $m^2/(s \cdot kV^2)$. When the leader head arrives at the cathode, the insulator is breakdown. $U(t)$ should contain both the voltage $U_L(t)$ caused by lightning current injection, and also the induced voltage $U_i(t)$. $U_L(t)$ can be calculated by the EMTP, and $U_i(t)$ is calculated by:

$$U_i(t) = 2.2 I_P^{0.4} h_c (1 - k_0 \frac{h_g}{h_c}) \quad (2)$$

where $I_P$ is the peak value of the lightning current, kA; $h_c$ is the average height of the wires, m; $h_g$ is the average height of earth wires, m; $k_0$ is the coupling coefficient. The formula originates from experimental data, and differs from the induced voltage formula proposed by regulations.

## III. RESULTS AND DISCUSSION

### *A. Present Lightning Performance*

Using above model, the LWLBS for two circuits was estimated. Then, combining with the actual ground flash density from the monitoring data of LLS, the lightning trip-out rate of each tower for more than one circuit is estimated, and as shown in Fig. 4. Without any additional lightning protection measures, the lightning trip-out rate of each tower can reach about 22 per 100km·a, because of the fairly high ground flash density along this transmission line. And this value is much higher than the value (2.23 per 100km·a) in operation specification issued by the south grid of china, and reflect the actual operating data. In this paper, five grades of lightning trip-out rate were stipulated, which was shown in Table I. The tower number in the grade V, IV, III, II, I is 2, 7, 9, 18, 14 respectively. Interestingly, the towers in the grades high than II are all with composite insulators because of the shorter dry arcing distance than that of glass insulators.

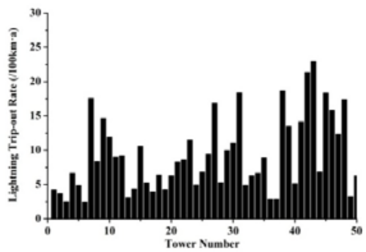



FIGURE IV. LIGHTNING TRIP-OUT RATE FOR MORE THAN ONE CIRCUIT FLASHING.

TABLE I. FIVE GRADES OF LIGHTNING TRIP-OUT RATE.

| Grade | Range of lightning trip-out rate (/100km·a) |
|---|---|
| I | 0~5 |
| II | 5~10 |
| III | 10~15 |
| IV | 15~20 |
| V | 20~25 |

### B. *Technology and Economy Comparison of Lightning Protection Measures*

Two kinds of protection devices and four kinds of layout schemes are discussed in this paper. The two devices are the insulator parallel gap (IPG) and the surge arrester (SA). The IPG has shorter dry arcing distance than insulator, therefore it will flashover prior to the insulator. If the IPG is arranged in just one circuit, the LWLBS of this circuit become lower, and the original symmetrical electric structure will not exist. With the help of unbalanced electric insulation, the lightning trip-out rate for two or three circuit will drop. The SA can be seen as a non-linear resistance, and it supplies a good discharge channel to reduce the lightning trip-out rate.

The first layout scheme is arranging IPG on all insulators in the I-circuit. This scheme will break the electric balance between I-circuit and II-circuit. The second layout scheme is arranging IPG on all glass insulators and SA on all composite insulators in the I-circuit. The third layout scheme is arranging SA on insulators in the I-circuit with trip-out grade higher than II and with composite insulator, and the rest insulators in the I-circuit are arranged IPG. The fourth layout scheme is just arranging SA on insulators in the I-circuit with trip-out grade higher than II. The estimating effects and costs of the four lightning protection measures are shown in Tab. II.

After applying these four lightning protection measures, the average lightning trip-out rate for more than one circuit will drop from 9.19 per 100km·a to 8.3, 4.64, 5.94, 6.41 per 100km·a . They all can reduce the lightning trip-out rate. The effect of the second layout scheme is the best, the average lightning trip-out rate will be reduced almost 50%, and it makes 70% towers in the first lightning trip-out grade, and no tower is in the fifth and the fourth grade. With the corresponding result, it will cost 60 IPGs and 90 SAs. Though the fourth layout scheme just reduces the average lightning trip-out rate about 30%, it cost lest, and just need 54 SAs. By using this layout scheme, the lightning trip-out grade of 94% towers will lower than III, and no tower is in the fifth and the fourth grade also. Synthesizing the technicality and the economy, the fourth layout scheme could be better than the other three schemes.

TABLE II. LIGHTNING PERFORMANCES AND COSTS OF THE FOUR LIGHTNING PROTECTION MEASURES.

| Layout Scheme | Tower number in each lightning trip-out grade | | | | | Average lightning trip-out rate for more than one circuit (/100km·a) | Cost | |
|---|---|---|---|---|---|---|---|---|
| | V | IV | III | II | I | | IPG | SA |
| Original | 2 | 7 | 9 | 18 | 14 | 9.19 | - | - |
| 1 | 2 | 7 | 8 | 13 | 20 | 8.3 | 150 | 0 |
| 2 | 0 | 0 | 3 | 12 | 35 | 4.64 | 60 | 90 |
| 3 | 0 | 0 | 3 | 23 | 24 | 5.94 | 96 | 54 |
| 4 | 0 | 0 | 3 | 29 | 18 | 6.41 | 0 | 54 |

## IV. CONCLUSIONS

In this paper, the lightning performances of treble-circuit transmission line were studies with the help of EMTP. Through taking a typical 110 kV transmission line as example, the technical economies of several lightning protection measures were discussed.

By setting insulator parallel gaps and surge arresters in one circuit of a treble-circuit transmission line to break the electric balance, the average lightning trip-out rate for more than one circuit flashing can be reduced. And the calculation results indicated that setting 60 IPGs and 90 SAs selectively according to the lightning performance and insulator type, the average lightning trip-out rate for more than one circuit flashing can be reduced 50%. If setting 150 IPGs indistinguishably, the average lightning trip-out rate for more than one circuit flashing just drops 9.7%.

Through setting SAs on the insulators in the I-circuit with trip-out grade higher than II, the average lightning trip-out rate for more than one circuit flashing will drop 30%, and all towers are below the fourth grade. This layout scheme just need 54 SAs, and has the best technology and economy.

## ACKNOWLEDGEMENTS

This work was financially supported by the State Grid Sichuan Electric Power Research Institute.

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