

Lightning Current Observation on UHVAC Transmission Lines by Improved Magnetic Steel Rod Method

Anfeng Jiang, Zhengcai Fu, Wei Sun, Zhen Xu

Key Laboratory of Power Transmission and Power Conversion Control

Shanghai Jiaotong University, Shanghai, 200030, China

Tel.: +86 18818238624, fax: +86 021 622932313

E-mail: anfeng@sjtu.edu.cn

Received: 12 May 2014 / Accepted: 29 August 2014 / Published: 30 September 2014

Abstract: Lightning stroke is the main threaten to the safe operation of UHVAC transmission lines. The magnetic steel rod method had been widely used as a traditional method for lightning accident and lightning current investigation in high voltage transmission lines. For the application of the magnetic steel rod method on UHVAC transmission lines, this paper proposed a practical and easy improved method of installing the magnetic steel rods directly on the transmission towers. The residual magnetism curve and accuracy verification of the proposed method was obtained through complex steel structure impulse current experiments. The magnetic steel rod location on UHVAC transmission tower was analyzed by the numerical analysis software MagNet. The application results of the proposed method on the first demonstration and test UHVAC transmission line is presented. The obtained datasets after one storm season was analyzed through Electromagnetic Transients Program. It is shown that the proposed method is feasible.
Copyright © 2014 IFSA Publishing, S. L.

Keywords: Lightning current observation, UHVAC transmission line, Magnetic field, Numerical analysis, Impulse current experiment, EMTP, Improved magnetic steel rod method.

1. Introduction

Due to rapid growing of power load demand and long distance of electric energy transmission, the first demonstration and test Ultra High Voltage Alternating Current (UHVAC) transmission line had been constructed in China [1]. The operating experiences in Russia and Japan show that lightning is the major hazard to the safe and stable operation of UHVAC transmission lines [2-3]. For example, the survey of UHVAC transmission line in Japan show that lightning trip out occupied 98 % of total number of system outages [3].

The lightning current parameters and stroke characteristics (stroke to the overhead ground wire or phase conductor) are the fundamental requirements

for rational lightning protection design of UHVAC transmission systems [2-10]. The lightning overvoltage and protection countermeasures of the first UHVAC transmission system in China are considerable designed [4-7]. In order to assess and control the lightning performance of UHVAC transmission systems more accurately in future, it is crucial to observe the lightning current parameters and lightning stroke characteristics on UHVAC transmission lines [8-10].

The parameters of lightning current obtained by the Lightning Location System (LLS) were used in design of UHVAC transmission system in China [4-7]. The minimum observational square grid 20 km×20 km was taken by the LLS, but the lightning attractive radius of the UHVAC

transmission line is only hundreds of meters [4-6], which means the lightning current of LLS is different from actual stroke on UHVAC transmission line. Therefore, the measurements of more accurate lightning current parameters on UHVAC transmission lines are needed.

The magnetic steel rod, magnetic tape, shunt resistance, current transformer, B-dot probe and Rogowski coil had been used for measuring lightning current on transmission lines [11-18]. Lightning rods with length 2~6 m were often raised up on transmission line tower tops and then the devices mentioned above were installed around them for the purpose to get an idea environment for the installation of the devices and relatively accurate measurement of the lightning current [12-18]. However, those lightning rods increase the equivalent height and change the electric field distribution of the towers. So the measured dataset of lightning current are different from the actual operational transmission lines. Compared with the method of direct measurement of lightning current by sensor coil with digital recording system and other methods of lightning accident and lightning current investigation [11-19], the magnetic steel rod method is economic and could be installed on a large number of transmission line towers.

In this paper, an improved magnetic steel rod method is proposed to observe the lightning current on the first demonstration and test UHVAC transmission lines. The new magnetic steel rods with preferable performance are adopted and the impulse current calibration experiment is carried out to obtain the residual magnetism curves. Based on numerical analysis of magnetic field distribution around transmission tower due to lightning current, the magnetic steel rods are directly installed on the transmission line towers' angle steel structures. The proposed method is applied to the first UHVAC transmission line in China. The observation results of one storm season are analyzed through the Electromagnetic Transients Program (EMTP).

2. The New Magnetic Steel Rods and Impulse Current Calibration Experiment

2.1. The Theory of Improved Magnetic Steel Rod Method

The improved magnetic steel rod method is based on the residual magnetism characteristic of magnetic steel rod. The lightning current recording principle of magnetic steel rod is shown in Fig. 1.

As shown in Fig. 1, lightning current pass through the conductor and induce a strong ambient magnetic field. Based on the Biot-Savart law, the lightning current I pass the conductor with length l , the current element $I dl$ generate magnetization intensity dB at the magnetic steel rod installation position P is given by

$$dB = \frac{\mu_0}{4\pi} \frac{I dl \sin \theta}{r^2} = \frac{\mu_0 I}{4\pi a} \sin \theta d\theta, \quad (1)$$

where a is the vertical distance between the conductor and magnetic steel rod, r and θ are shown in Fig. 1. Then B at the position P generated by current through the whole conductor is given by

$$B = \int_{\theta_1}^{\theta_2} \frac{\mu_0 I}{4\pi a} \sin \theta d\theta = \frac{\mu_0 I}{4\pi a} (\cos \theta_1 - \cos \theta_2), \quad (2)$$

If the conductor length $l \gg a$, than the magnetic field intensity H is given by

$$H = \frac{B}{\mu_0} = \frac{I}{2\pi a}, \quad (3)$$

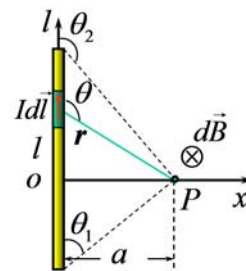


Fig. 1. The principle of improved magnetic steel rod method.

Based on the equation (3) and flow chart in Fig. 2, the amplitude and polarity of the lightning current could be obtained by measuring the residual magnetism curve of the magnetic steel rod, and then the lightning current parameters and stroke characteristics will be concluded.

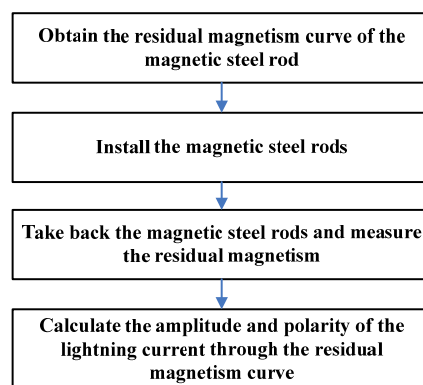


Fig. 2. The flow chart of improved magnetic steel rod method.

2.2. The Residual Magnetism Curve of the Magnetic Steel Rod

Comparing with the previous magnetic steel rod, the new developed magnetic steel rods used in this

method have larger measuring range, better degree of linearity, high saturation level, more stability and sensitivity, which make the proposed method more accurate than previous.

The impulse current experiment is used to test and calibrate the residual magnetism curve of the magnetic steel rod. The simulated lightning current is generated by the output exponential wave current of

Impulse Current Generator. The circuit schematic diagram of Impulse Current Generator is shown in Fig. 3, where T is the charging transformer, D is the silicon rectifier stack, C is impulse capacitor, R is the adjustable resistance, L is the adjustable inductance, G is the discharge air gap, O is the test object, S is the current diverter, S1~ S4 are the measuring cables, OSC is digital oscilloscope TDS3012B.

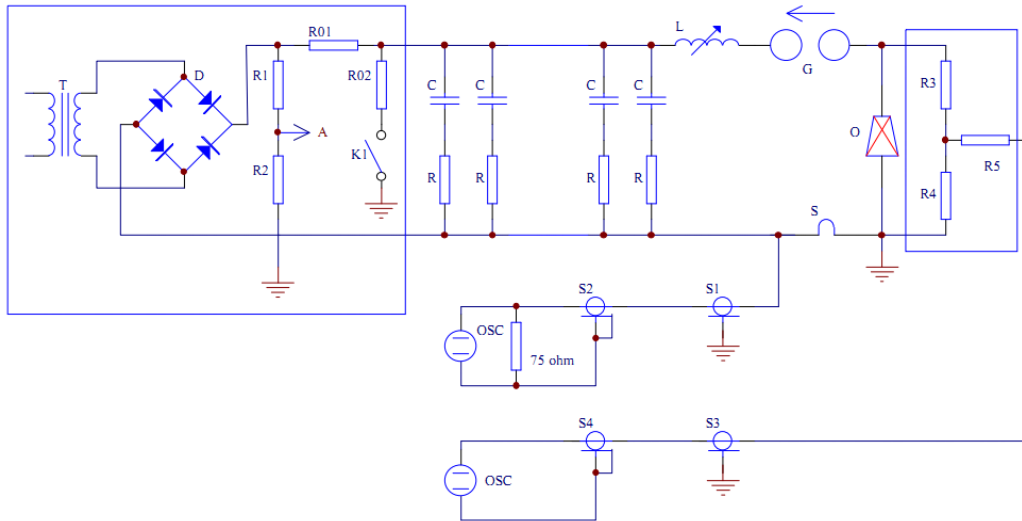


Fig. 3. The circuit schematic diagram of impulse current generator.

In order to eliminate the influence of magnetic field generated by the return current on lead wire, a shielded cage (2 m height and 1 m radius) welded by the round steel (Φ 1 cm) as Fig. 4 was designed as the conductor. The magnetic steel rod was orthogonally installed on the central conductor of the shielded cage and the exponential wave $8/20 \mu\text{s}$ current generated by the Impulse Current Generator was injected to the top conductor of the cage. A digital Gauss meter KANETEC TM701 was used to measure the residual magnetism of the magnetic steel rod. The Gauss meter has measuring range 0~3000 mT and measurement accuracy 0.01 mT, which is more accurate than Compass meter used in previous magnetic steel rod method.

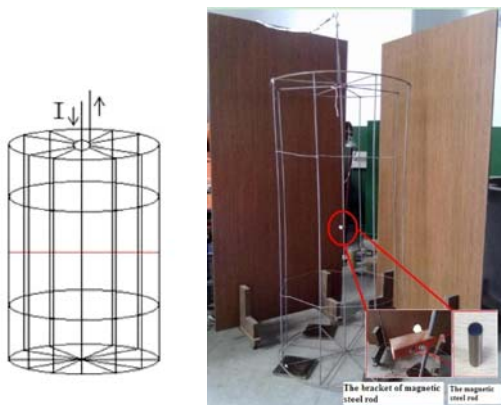


Fig. 4. The sketch map (left) and photo (right) of shielded cage.

The amplitude of injected current and distance between the magnetic steel rods to the central conductor had been changed during each test. Fig. 5 shows the results of these experiments.

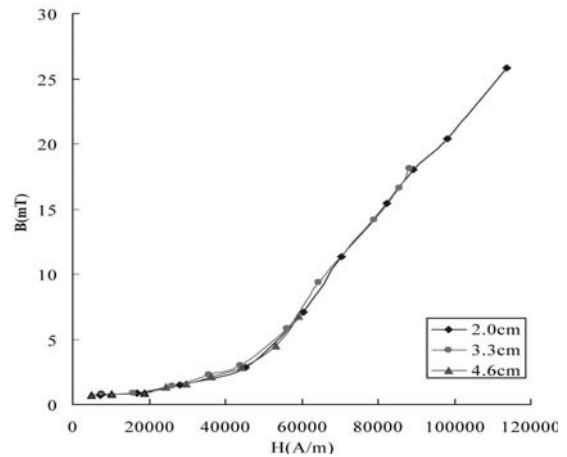


Fig. 5. The residual magnetism curve of the magnetic steel rod with different distance between the magnetic steel rod and the central conductor.

As shown in Fig. 5, the residual magnetism curve of the magnetic steel rod show little correlation to the distance between the magnetic steel rod and the central conductor in the range from 2 cm to 4.6 cm, the magnetic steel rods have good degree of linearity in the current range.

Because it is not practical to take down the magnetic steel rod immediately after one lightning stroke, which means the magnetic steel rod may suffer more than one lightning current during the operation period. The magnetic steel rod could only record the largest current. In order to evaluate the cumulative effect of lightning current to the magnetic steel rod, an 8/20 μ s 10.8 kA current was exerted 15 times to the same magnetic steel rod. Fig. 6 shows the results of this experiment.

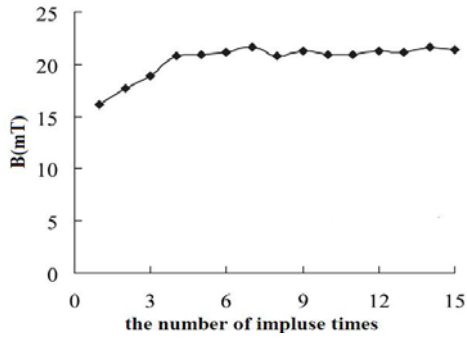


Fig. 6. The residual magnetism cumulative effect curve of the magnetic steel rod.

As shown in Fig. 6, the ratio between the final and initial residual magnetism is about 1.3 and this ratio keep stable in the linear region of the residual magnetism calibration curve.

2.3. The Accuracy Experiment of the Proposed Method

In order to test and verify the accuracy of the magnetic steel rod method applied to the complex steel structure, a complicated steel frame shown in Fig. 7 was constructed. Four magnetic steel rods were orthogonally installed on the middle of the 37~40 positions of conductors and the impulse current was injected to the lightning rod.

The result obtain by this method was compared to the direct measurement of standardized current diverter.

The total injected current measured by the current diverter was 18.5 kA and the four summed current obtained from the proposed method was 18.0 kA, which means for a single impulse current, the measurement error of proposed magnetic steel rod method can be less than 3 %.

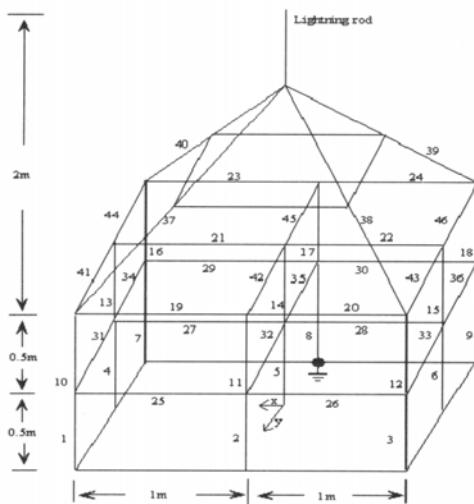


Fig. 7. The sketch map (left) and photo (right) of the complicated steel frame used for test and verify the accuracy of the magnetic steel rods method.

3. Numerical Analysis of the Magnetic Steel Rod Location on UHVAC Transmission Tower

3.1. The Influence of Steel Frame of the Transmission Tower

In the previous method as shown in chapter 2.1, only the magnetic field intensity of round steel frame was taken into account when install magnetic steel rod around the lightning rod on the transmission line tower [11-18]. But the actual steel frames of the

UHVAC transmission towers are angle steel bars, the influence of steel frame need to be analyzed.

The infinite angle steel bar can be approximated as two infinitely long current-carrying conductor plate into a 90° phase formed, so the magnetic field intensity distribution formula of the infinitely long angle steel bar could obtained through the Biot-Savart law. Because the obtained formula is so complicated and the thickness of the angle steel bar is not taken into consideration, the numerical analysis of the electromagnetic field needs to be adopted.

The MagNet is the magnetic field simulation software based on the Finite Element Method (FEM).

The infinite round steel bar model (radius 7 cm) and angle steel bar model (width 14 cm, thickness 1 cm) were built in MagNet, and the 8/20 μ s, 10 kA impulse current was adopted as the simulated excitation. Fig. 8 shows the simulation results.

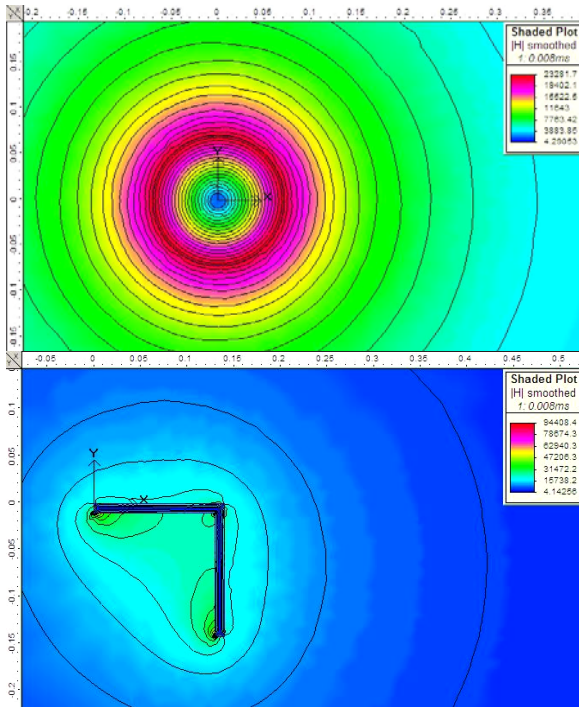


Fig. 8. The magnetic field intensity distribution of the round steel bar and angle steel bar.

The comparison between the simulated results as shown in Fig. 8 and the theoretical formula show that in order to use the theoretical formula of round steel to calculate the magnetic field of the angle steel, the magnetic steel rod should be placed 2 cm from the surface of angle steel, where the difference between round and angle steel is 1.5 %.

3.2. The Simulated Installation Location of Magnetic Steel Rods

In the previous magnetic steel rods method, only the magnetic field intensity around the lightning rod on the transmission line tower top was considered. However, the total magnetic field intensity at the truss of towers' angle steel structures and fittings is the sum of magnetic field intensity of other tower steel structures when the lightning current pass through them. So it is critical to analyze the relationship of the magnetic field intensity and lightning current of transmission tower structure where the magnet steel rods are located.

The model of typical UHVAC transmission line tower and its angle steel structures was build according to the actual parameters through the MagNet as shown in Fig. 9. An 8/20 μ s, 10 kA

current I was used as the excitation. The magnetic field intensity at each of potential location of the magnet steel rods was calculated.

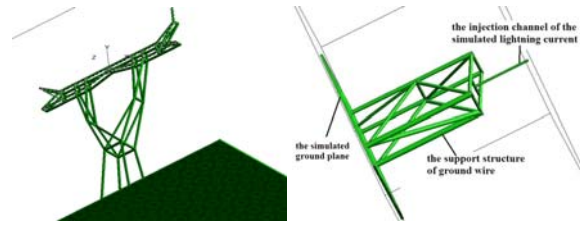


Fig. 9. The model of UHV transmission line tower (left) and its angle steel structures (right) section in MagNet.

The obtained magnetic field intensity H is related to the distance x (magnetic steel rod between the center of the current injection channel) under each different vertical distance z (location of the magnetic steel rod between the simulated ground plane) are obtained, the fitting curves and equations were analyzed by the Origin software. For example, the fitting equation and curve magnetic field intensity H at vertical distance $z=0.6$ m is shown in Fig. 10:

$$H = I(0.24737 + \frac{0.007}{x - 0.04}), \quad (4)$$

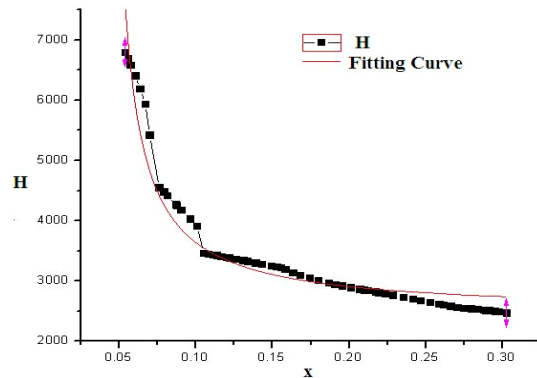


Fig. 10. The magnetic field intensity fitting curve of magnetic steel rod.

Based on the fitting equation obtained through MagNet, the proposed improved magnetic steel rod method could be used to derive the value of the total lightning current amplitude at different location of the magnetic steel rod on the transmission line towers' angle steel structures and fittings.

4. The Actual Installation of the Magnetic Steel Rods

Because the first demonstration and test UHVAC transmission lines is so long and with many towers, it is not practical to install the magnetic steel rods on all transmission towers. Therefore the UHVAC

transmission lines section in Henan province is selected. The selected towers of the magnetic steel rods installation are based on lightning stroke data in year 2002~2009 obtained by the Lightning Location System (LLS) in Henan province and operational experiences of nearby Extra High Voltage (EHV) transmission lines, the selection criteria are:

- 1) The isokeraunic level more than 30 days/year;
- 2) The ground flash density more than 2.5 times $/(km^2 \times year)$;
- 3) The distribution of lightning stroke median peak current is larger than 35 kA;
- 4) The lightning trip out was record on nearby EHV transmission lines.

If the transmission towers could satisfy the above four criteria simultaneously, the magnetic steel rods will install on the towers. Finally, 69 straight towers and 14 strained angle towers were selected. The typical installation locations of magnetic steel rods are shown in Fig. 11 and Fig. 12.

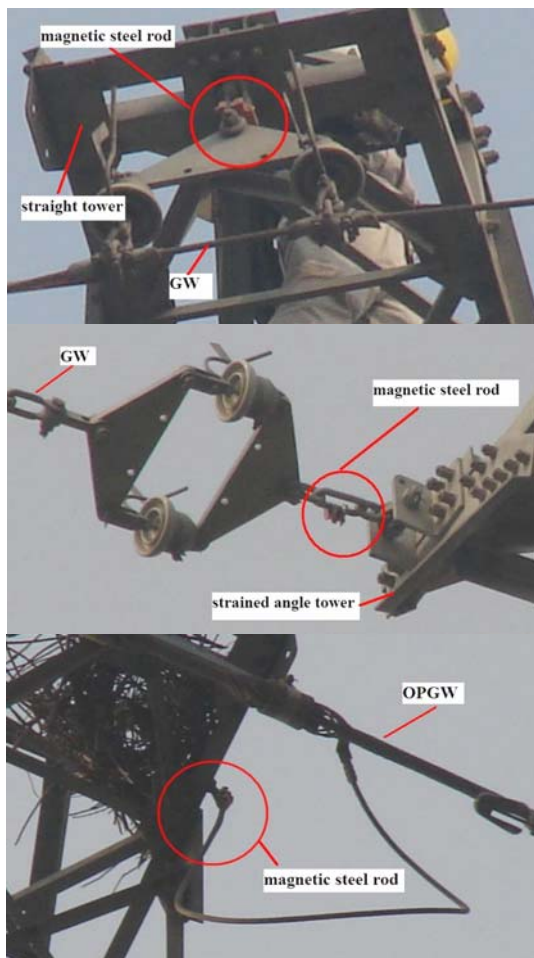


Fig. 11. The typical location of the magnetic steel rods on the ground wire of the UHVAC transmission towers.

As shown in Fig. 11, the magnetic steel rods on ground wire and optical fiber ground wire (OPGW) of the straight towers and OPGW of the strained angle towers could measure the lightning current

flow into the tower, and the ones on the ground wire of the strained angle towers could measure the lightning current through the ground wire. As shown in Fig. 12, in order to measure the lightning current through insulator due to shielding failure or back flashover trip out, the insulation side of conductor was selected. Finally, there were 887 magnetic steel rods installed, 662 of them were on the straight towers and 225 on the strained angle towers.

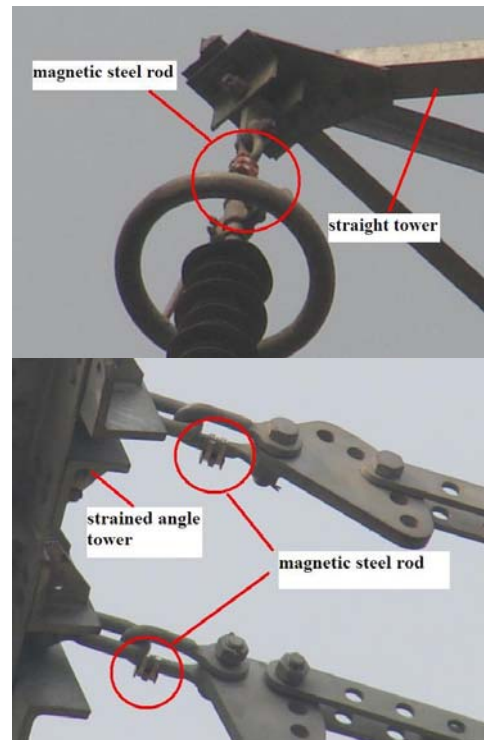


Fig. 12. The typical location of the magnetic steel rods on the insulation side of the UHV transmission towers.

5. Analysis of the Observation Results

After one storm season, 358 magnetic steel rods on 30 towers had been taken down to analysis the lightning stroke incidences, among them 22 were straight towers (10 magnetic steel rods on average) and 8 were strained angle towers (20 magnetic steel rods on average). The magnetic steel rods with residual magnetism larger than 5 mT were considered on the lightning current passed conductors, and there were 29 magnetic steel rods on 22 straight towers and 21 ones on 8 strained angle towers correspond to this criterion. Because there was no lightning trip out incidence during the operation, the magnetic steel rod on the insulation side of the conductor was not analyzed. Based on the improved magnetic steel rod method proposed in section 2 and section 3, the lightning current amplitude and polarity of conductor correspond to each magnetic steel rod installation location was calculated. The calculated results are shown in Fig. 13 and all measured lightning current were negative polarity.

In order to analyze the lightning current distribution on the section of UHVAC transmission line, Electromagnetic Transients Program (EMTP) is adopted to build the transmission line lightning stroke model [19]. The transmission line with twelve spans is represented by the frequency-dependent J. Marti model [20]. The phase conductors are eight-bundle LGJ-500/35 aluminum steel-reinforced conductor with a diameter of 30 mm and spacing 450 mm, the ground wires are type JLB20A-170 aluminum sheathed stranded conductor with a diameter of 17 mm. The sag length of conductor and ground wire are 18.97 m and 9.16 m, respectively. The UHVAC source is connected to the phase conductor. Two resistor circuits are connected to the ends of the model line in order to eliminate the reflection of travelling waves [20]. The multistory surge impedance is used as tower model. The current dependent model recommended by CIGRE [20] is adopted as the tower grounding model. The most widely used Heidler model is adopted as the lightning current source [19], the waveform 3.83/77.5 μ s recommend by IEEE Std. 1243 [21] is used. The parallel lightning channel surge impedance is set as 400 Ω [19].

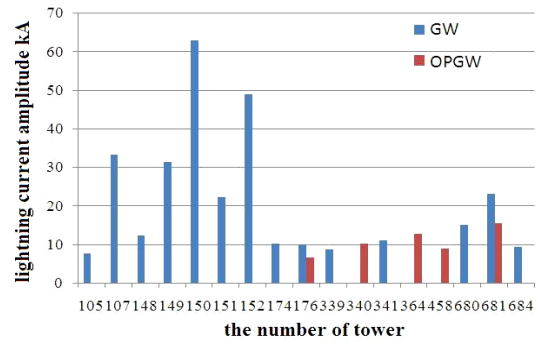


Fig. 13. The measured lightning current amplitude corresponds to different location on of the UHVAC transmission lines.

All the measured the lightning current distribution were analyzed. Take the tower from No. 147 to No. 153 section of UHVAC transmission line as an example. Based on the above results and parameters of these transmission line and towers, the lightning stroke points were obtained. Fig. 14 shows the calculated results and the currents were negative polarity.

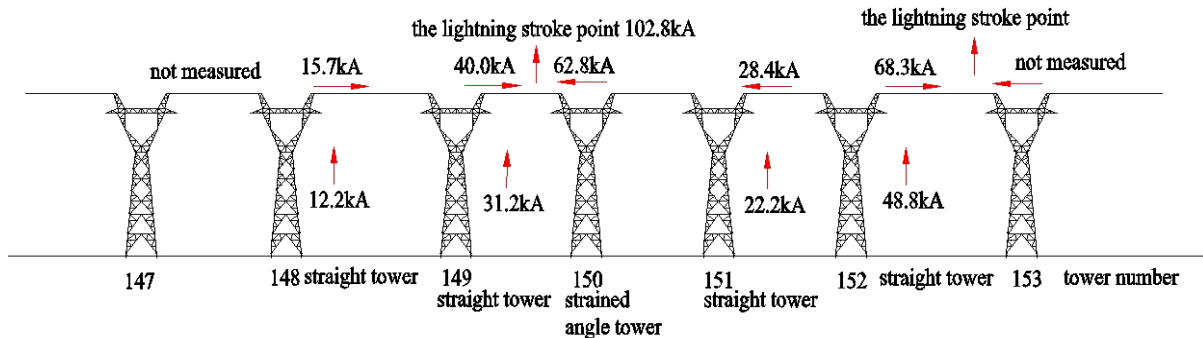


Fig. 14. The schematic diagram example of lightning stroke analysis between tower 147 and 153.

As shown in Fig. 14, there were at least three stroke points on this section, two of them were in the mid-span (one of the strokes was at 275 m from the No. 150 tower) and one was on the No. 151 tower top.

6. Conclusions

In this work, based on residual magnetism impulse current calibration experiment and magnetic field numerical analysis of the magnetic steel rod location on UHVAC transmission tower, an improved magnetic steel rod method is proposed. For experiment of a single impulse current injected to a complex steel structure, the measurement error of proposed magnetic steel rod method can be less than 3%. The fitting equation of magnetic steel rod location on UHVAC transmission tower and magnetic field intensity is obtained by MagNet software. The proposed method is applied to the first

demonstration and test UHVAC transmission line. After one storm season operation, the amplitude and polarity of lightning current is obtained, the current distribution on the transmission line is analyze through Electromagnetic Transients Program. The results show the proposed method is feasible and could be used as basic and economic measurements of lightning current observation on transmission lines.

References

- [1]. D. C. Huang, Y. B. Shu, J. J. Ruan and Y. Hu, Ultra high voltage transmission in China: developments, current status and future prospects, *Proceedings of the IEEE*, Vol. 97, Issue 3, 2009, pp. 555-583.
- [2]. I. P. Vereshchagin, W. H. Wu, The analysis of lightning protection for EHV and UHV transmission lines in Russia, *High Voltage Engineering*, Vol. 24, Issue 2, 1998, pp. 76-79 (in Chinese).

- [3]. S. Taniguchi, T. Tsuboi, S. Okabe, Observation results of lightning shielding for large-scale transmission lines, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 16, Issue 2, 2009, pp. 552-559.
- [4]. B. G. Wei, Z. C. Fu, H. Y. Yuan and P. Y. Du, An improved leader progression model for the analysis of the shielding performance of 1000 kV UHVAC transmission lines, *European Transactions on Electrical Power*, Vol. 20, 2010, pp. 327-335.
- [5]. Z. P. Liang, Y. S. Li, H. C. Hu and J. B. Jia, Design of UHV AC transmission line in China, *European Transactions on Electrical Power*, Vol. 22, 2012, pp. 4-16.
- [6]. D. X. Gu, P. H. Zhou, M. Dai, M. H. Xiu and H. W. He, Overvoltages and insulation coordination of 1000-kV AC transmission systems in China, *European Transactions on Electrical Power*, Vol. 22, 2012, pp. 83-93.
- [7]. Y. Q. Wu, C. H. Yan, B. J. Li, and J. Fang, Design and research of UHV AC substation, *European Transactions on Electrical Power*, Vol. 22, 2012, pp. 17-32.
- [8]. J. Takami, S. Okabe, E. Zaima, Lightning surge overvoltages at substations due to backflashover with assumed lightning current waveforms based on observations, *IEEE Transactions on Power Delivery*, Vol. 25, Issue 4, 2010, pp. 2958-2969.
- [9]. S. Okabe, J. Takami, Occurrence probability of lightning failure rates at substations in consideration of lightning stroke current waveforms, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 18, Issue 1, 2011, pp. 221-231.
- [10]. S. Taniguchi, T. Tsuboi, S. Okabe, Y. Nagarak, J. Takami and H. Ota, Improved method of calculating lightning stroke rate to large-sized transmission lines based on electric geometry model, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 17, Issue 1, 2010, pp. 53-62.
- [11]. K. E. Crouch, Calibration test on magnetic tape lightning current detector, USA, NASA contractor report, 3270, *National Aeronautical and Space Agency*, 1980.
- [12]. H. Haruki, M. Sunaga, R. Kimata and J. Katoh, Development of a lightning current waveform measuring system for 500 kV overhead transmission lines, *IEEE Transactions on Power Delivery*, Vol. 4, Issue 3, 1989, pp. 1891-1896.
- [13]. T. Narita, T. Yamada, A. Mochizuki, E. Zaima and M. Ishii, Observation of current waveshapes of lightning strokes on transmission towers, *IEEE Transactions on Power Delivery*, Vol. 15, Issue 1, 2000, pp. 429-435.
- [14]. W. J. Feng, Q. Chong, L. X. Bing, Y. Y. Che, L. L. Fan and Y. L. Wang, Use of magnetic links to measure the maximum rate-of-rise of lightning currents, *IEEE Transactions on Power Delivery*, Vol. 22, Issue 4, 2007, pp. 2445-2449.
- [15]. J. Takami, S. Okabe, Observational results of lightning current on transmission towers, *IEEE Transactions on Power Delivery*, Vol. 22, Issue 1, 2007, pp. 547-556.
- [16]. W. J. Zhou, T. Wang, J. H. Yu, S. H. Zhang and L. J. Cao, Study on real-time lightning current monitoring system for overhead wire, in *Proceedings of the International Conference on High Voltage Engineering and Application*, Chongqing, China, November 9-13, 2008, pp. 629-632.
- [17]. D. T. Silva, J. L. Silvino, J. C. de Melo, Detection and location of direct lightning strokes to overhead power transmission lines by measuring currents from shield wires, in *Proceedings of the IEEE/IAS International Conference on Industry Applications*, Sao Paulo, Brazil, 8-10 November, 2010, pp. 1-6.
- [18]. C. G. Yao, Q. B. Xiao, Y. Mi, Y. Yuan, C. X. Li and W. X. Sima, Contactless measurement of lightning current using self-integrating B-dot probe, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 18, Issue 4, 2011, pp. 2445-2449.
- [19]. J. A. Martinez, F. C. Aranda, Lightning performance analysis of overhead transmission lines using the EMTP, *IEEE Transactions on Power Delivery*, Vol. 20, Issue 3, 2005, pp. 2200-2210.
- [20]. IEC Insulation co-ordination—Part 4: Computational guide to insulation co-ordination and modeling of electrical networks, *IEC Std. 60071-4*, Jun. 2006.
- [21]. IEEE Guide for Improving the Lightning Performance of Transmission Lines, *IEEE Std. 1243-1997*, *IEEE*, Jun. 1997.