Indonesian Journal of Electrical Engineering and Computer Science
Vol. 37, No. 2, February 2025, pp. 689~699
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v37.i2.pp689-699

Proposed strategies for lightning performance improvement of 35 kV distribution lines in Vietnam

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Article Info

Article history:

Received Apr 24, 2024
Revised Sep 11, 2024
Accepted Sep 30, 2024

Keywords:

EMTP-RV
Finite element
Lightning strikes
Shield wire
Surge arrester

ABSTRACT

Lightning strikes frequently cause power outages on 35 kV distribution lines in Vietnam. These lines was normally protected with a sparse density of surge arrester and typically do not make use of shield wire. On the other hand, a single rod, that is frequently used as the grounding electrode, is not suitable for some region with high value of soil resistivity. Therefore, it is of particular of interest to investigate the solutions to protect the medium voltage lines from the back-flashover due to lightning strikes by analyzing the impact of the grounding impedance, the surge arrester density and the installation of the shield wire. The finite element method and the electromagnetic transient program EMTP-RV are combined in this work to propose techniques for increasing the critical flashover current of 35 kV lines in Hanoi city. The obtained results showed that the installation of shield wires combined with high density of surge arrester and reduced grounding impedance value can achive a very significant improvement of the overall lightning performance of the line.

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1. INTRODUCTION

Due to increasing customer demands, distribution lines must ensure a high level of power supply reliability. In order to guarantee this, electricity companies frequently implement many solutions to avoid economic losses due to the outages. However, statistics from China, Japan, and Malaysia indicate that lightning is the primary cause of power outages [1], [2], causing anywhere from 40 to 70% of all outages [3]. Vietnam, which has a high lightning density, also has a high rate of lightning-related incidents on the distribution grid. Figure 1 depicts a high rate of lightning-related incidents in Hanoi from 2019 to 2021, according to statistics of three power companies.

There are currently many effective methods for reducing the frequency of lightning-related power outages, which can be broken down into solutions focusing on lightning protection system components such as: grounding systems, surge arrester, and shield wire installation. The most widely used lightning protection strategies of power distribution systems are based on the implementation of these devices.

According to Omididora [4], the installation of shield wires improves the lightning performance of 20 kV medium voltage lines in Finland. The conductors of medium-voltage lines are subjected to voltages induced by lightning striking the surrounding trees as they pass through areas with a lot of trees. According to research [4], when the shield wire is grounded, the induced voltage on the conductor is reduced by 29%. In addition, the conductor is shielded from discharge from nearby trees or structures by shield wire, which limits the induced voltage and protects it from direct lightning strikes.

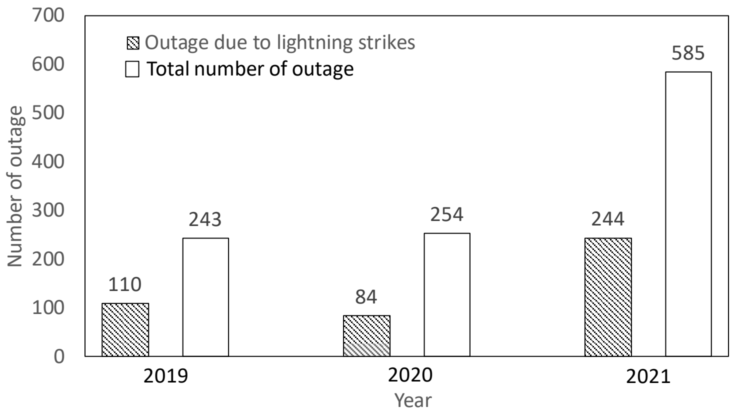


Figure 1. Statistics on the number of power outages due to lightning over the total number of power outages of 3 power companies in Hanoi

Cao *et al.* [5] analyzed many aspects to optimize lightning protection design for 10 kV medium voltage lines using shield wires. The authors demonstrate that the best lightning protection performance is achieved when the shield wire is grounded at each tower location. Mikropoulos and Tiovilis [6] demonstrated that an optimal lightning protection system can be achieved with the proper placement of the surge arresters relative to the phase conductors. Lines equipped with surge arresters are estimated to have a discharge rate of approximately 0.05 discharges/100 km/year.

Omidiora and Lehtonen [7] shows that in areas with high lightning intensity, the solution of using shield wire for medium voltage lines is the most suitable because surge arresters cannot eliminate overvoltage when lightning strikes directly on the phase conductor. Atmospheric overvoltage on mixed overhead/underground cable lines is discussed in reference [8] which clearly shows that the installation of surge arresters at both ends of the cable reduces overvoltage.

Research results in the document [9] show that in areas with high earth conductivity and low insulation level (150 kV), or low earth conductivity and high insulation level (300 kV), the optimal distance between surge arrester is about 400m. In areas with low soil conductivity and insulation levels, the distance between surge arresters can be reduced to 200m. Document [10] shows that grounding resistance, wave front time and lightning surge amplitude are important parameters when analyzing the voltage drop value on the insulation and the frequency of back flashover. Literature [11] shows that the frequency of back flashover is reduced when the ground resistance is reduced as low as possible.

However, the relationship between grounding resistance and surge arrester has been shown that very low levels of grounding resistance can pose a risk of damaging the surge arrester, depending on the location of the lightning strike and characteristic curve of the surge arresters [12]. Research in Japan for the 6.6 kV medium voltage grid shows that incidents of surge arrester damage due to high released energy levels compared to the surge arrester tolerance still often occur [13].

On the other hand, research results in [14] show that reducing the resistivity and dielectric constant of soil allows reducing the frequency of power outages by 13-32% on the distribution grid. Some other studies such as [15] show that using a double ground wire structure for steel electric towers is optimal. Paulino *et al.* [16] demonstrated that the waveform of the lightning current is influenced by the soil resistivity, the length of the ground wire and the distance between the lightning and phase conductors. Lightning waveforms, installation locations of protection systems and lightning locations are clarified to indicate the severity of lightning in the literature [17].

As a result, these studies have offered a wealth of information and numerous suggestions for enhancing lightning performance of the distribution lines. However, these recommendations exclusivly concentrate on a single solution and do not take into account all aspects of the lightning protection system. Therefore, this study aims to propose techniques to improve the lightning performance for medium voltage lines in Vietnam by simultaneoustly applying three solutions: reducing the grounding impedance, increasing surge arrester density and installing the shield wire. The obtained results should be the sugesstion for the utilities in Vietnam to modify the current regulations related to the surge arrester density, grounding structure and the implementation of shield wire for the medium voltage lines. This paper consists of 04 sections: the first one is an introduction, the second one introduces the method, the third one is the results of application and discussion, the last one is conclusion.

2. METHOD

Reinforced concrete towers without shield wire are widely used for 35 kV distribution lines in Vietnam. According to the regulation, surge arresters are installed with a density of 3 single phase surge arresters for each 6 spans to protect these lines against lightning strike. These surge arresters use the same external ground wire with the tower to conduct the lightning current to the grounding electrode. A single rod is used as grounding electrode as illustrated in Figure 2.

The evaluation of the lightning performance is based on the estimation of the critical flashover current, which is the minimum lightning current intensity required to produce a flashover in case of direct strike on the tower. This section introduces the calculation procedures based on the simulation using the EMTP-RV electromagnetic transient program to obtain the value of this critical flashover current. In addition to the simulation by EMTP-RV, the finite element method using Comsol Multiphysics is applied to calculate the inductance and capacitance parameters of the grounding electrode to take into account the transient response of the electrode at high frequency. The flow-chart of the calculation procedure of the critical flashover current is presented in the Figure 3.

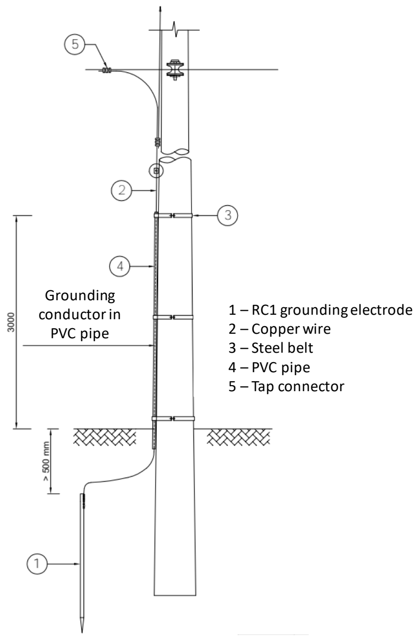


Figure 2. Reinforced concrete tower structure for 35 kV distribution lines in Vietnam

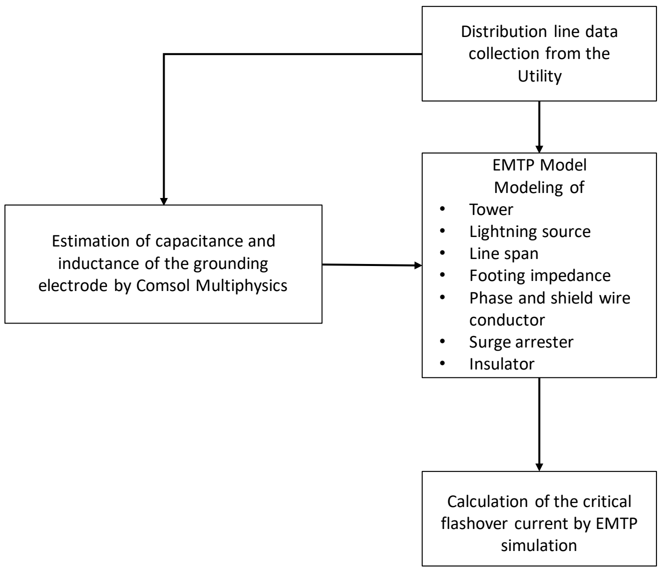


Figure 3. Calculation procedure of the critical flashover current

2.1. Modeling of lightning protection system
2.1.1. Reinforced concrete tower and the external grounding wire models

The reinforced concrete tower and the external grounding wire are modeled by two surge impedance in parallel as shown in Figure 4.

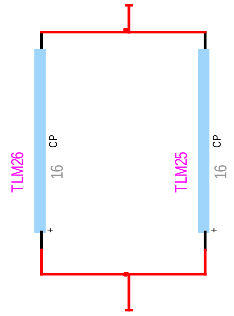


Figure 4. Reinforced concrete tower and external ground wire model

Surge impedance value of the reinforced concrete tower is calculated as below [18]:

$$Z_T = 60 * (\ln\frac{\sqrt{2}*2h}{r_e} - 2) \quad (1)$$

With h is the height of the concrete tower, r_e is the equivalent radius of the concrete tower taking into account the conical shape with the radius increasing toward the bottom. The equivalent radius of the concrete tower is calculated as following [18]:

$$r_e = r_T^{1/3} * r_B^{2/3} \quad (2)$$

Surge impedance of the external ground wire is calculated by [19]:

$$Z_{gc} = 60 * ln\left(\frac{h}{er}\right) - k * ln(1 + \frac{r_e}{D}) \quad (3)$$

With h is the length of the external ground wire, e is a natural constant, r is the radius of the external ground wire, r_e is the equivalent radius of the concrete tower, D is the distance between the concrete tower surface and the external ground wire, k constant is determined in (4) [19]:

$$k = 0.096 * r_e + 13.95 \quad (4)$$

2.1.2. Grounding electrode model

DC resistance of the grounding electrode is normally used for lightning performance analysis without considering the transient response at high frequencies under lightning impulse current condition. This study suggest therefore a combined model including a nonlinear resistance model taking into account the soil ionization and high-frequency model considering the inductance and the capacitance of the grounding electrode. The combined model of the grounding electrode is presented in Figure 5.

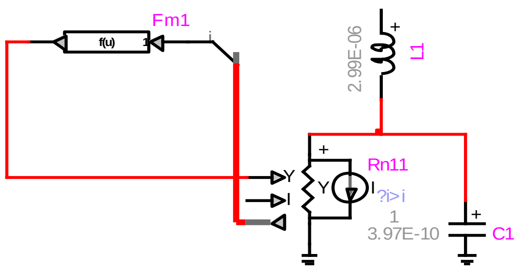


Figure 5. Combined model for the grounding electrode

Nonlinear resistance value that depends on the injected current is determined by the (5) [20]:

$$R(t) = \frac{R}{\sqrt{1+\frac{I(t)}{I_g}}} \quad (5)$$

$$I_g = \frac{E_0\rho}{2\pi R^2} \quad (6)$$

With E_0 is the critical electric strength of the soil (typically in range of 300 to 1500 kV/m), ρ is the soil resistivity, R is the dc resistance of the grounding electrode. The data of soil resistivity and dc resistance at each tower were experimentally measured by Hanoi power company in this work.

The inductance and the capacitance of the grounding electrode at 50 Hz power frequency are calculated by the finite element method using Comsol Multiphysics. These calculations are presented in the next section.

2.1.3. Line insulator model

Line insulator is described by the air gap shown in Figure 6. Flashover across the insulator due to lightning overvoltage occurs when the voltage exceeds the basic impluse level (BIL) value of 195 kV for 35 kV line insulator. The value of the critical flashover current is taken into account when the flashover occurs.

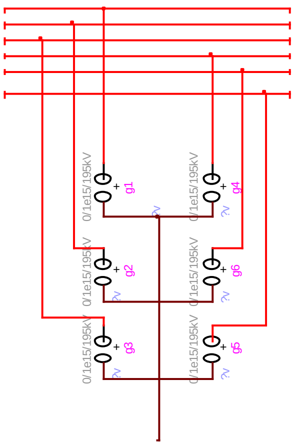


Figure 6. Insulator model for 35 kV distribution line

2.1.4. Span model

The FD element which is suitable for multi-frequency phenomena was used to simulate the span of conductors and shield wire of the 35 kV double circuit lines. This model is more accurate than the Constant Parameters (CP) line model. The FD element model is introduced in Figure 7

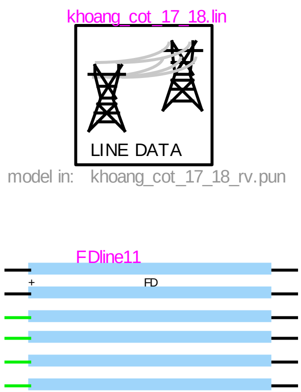


Figure 7. FD model for 35 kV distribution line span

2.1.5. Lightning impulse current source model

The lightning current source model as shown in Figure 8 according to the Cigré concave shape [21] is used to describe the process of injecting lightning current into 35 kV distribution lines. The impedance of the lightning channel is 400Ω, the waveform used in the simulation is 8/20μs. The current source was respectively injected into each tower in order to estimate the critical flashover current at these towers.

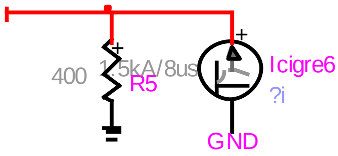


Figure 8. Lightning impulse current source model

2.1.6. Surge arrester model

The IEEE model for the surge arrester as shown in Figure 9 was used with the main parameters of the 35 kV surge arrester reported in Table 1. In the time-domain solution this device is a nonlinear function. It is solved through the iterative process of EMTP until convergence

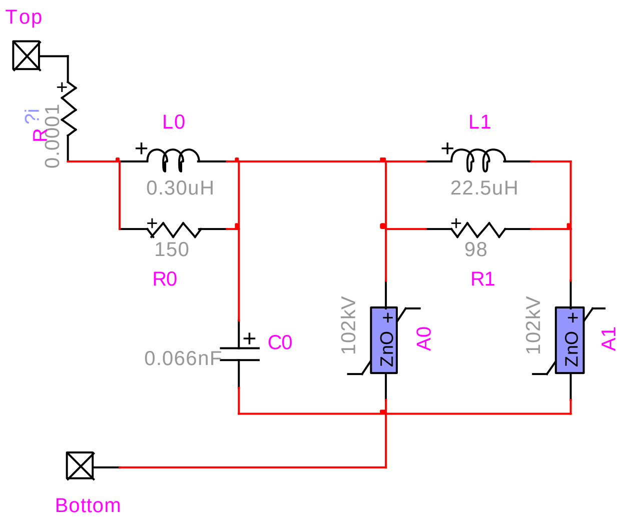


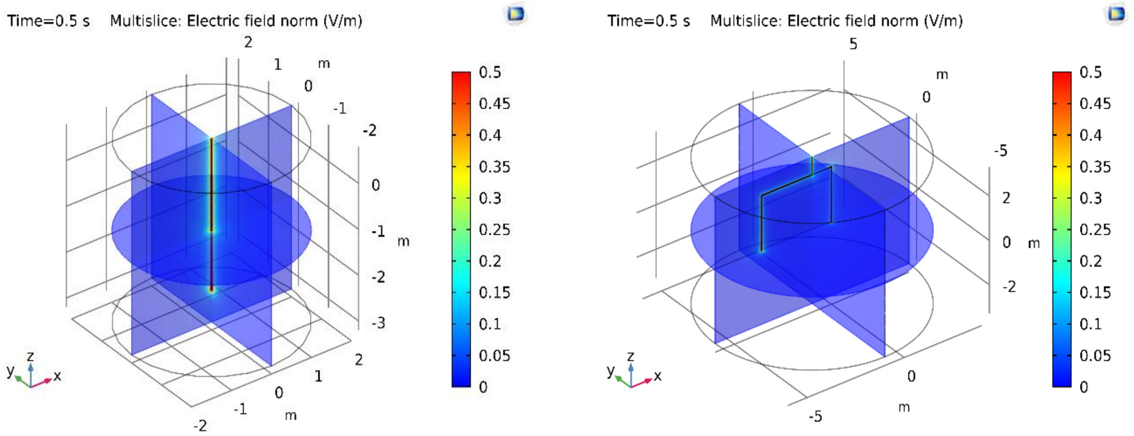
Figure 9. IEEE surge arrester model

Table 1. Characteristic of 35 kV surge arrester in simulation

Characteristic	Parameter
Maximum continuous operating voltage (kV)	29
Rated voltage (kV)	36
Energy absorption (kJ/kV)	1.83
Lightning Impulse Residual voltage for 5kA, 8/20 μs	102

2.2. Grounding electrode parameter calculation by the finite element method

As mentioned in the grounding electrode model content in section 2.1, the inductance and capacitance of the grounding electrodes at 50 Hz power frequency are calculated by the finite element method using Comsol Multiphysics to take into account the high-frequency response of the grounding electrode. The Electric Currents module in Comsol Multiphysics was used to calculate the capacitance of electrodes placed in the ground with boundary conditions including Terminal (Voltage = 1*sin(314t) V) on the electrode, Ground on the sides and bottom of the cylinder, Electric Insulation boundery is on the top of the cylinder. Soil resistivity values were measured experimentally at each tower location. Electric field distribution around the RC1 electrode (1 rod) and RC2 electrodes (2 rods – the proposed improvement of the grounding electrode structure) of the 35 kV distribution lines at 0.5s is consecutively presented in Figure 10. Figures 10(a) illustres the electric field distribition of the RC1 electrode and Figure 10(b) presentes the last one for the RC2 electrode.



(a) (b)

Figure 10. Electric field normalized distribution on the grounding electrode at 0.5s and 50Hz power frequency (a) RC1 and (b) RC2

Capacitance of these electrodes was calculated by the following formulas:

$$C = \frac{2*W_e}{U^2} \tag{7}$$

With W_e is electric energy, U is the nominal voltage value on the electrode.

Then, the Magnetic Fields module with Coil boundary is assigned to the electrodes to calculate the inductance of these electrodes at the frequency of 50Hz. The inductance and capacitance values of the electrodes calculated using the finite element method are then inserted into the grounding electrode model in EMTP-RV to simulate the transient response of the electrode at high frequencies when dissipate lightning current. This combined model obtains higher accuracy than using DC resistance model.

2.3. Simulation setup

A section of ten towers has been modelled to take into consideration the effect of successive reflection of neighbouring towers. Lightning strikes are applied at the tower top and the critical flashover current is calculated for each tower position. The EMTP modelling of the considered section is presented in Figure 11.

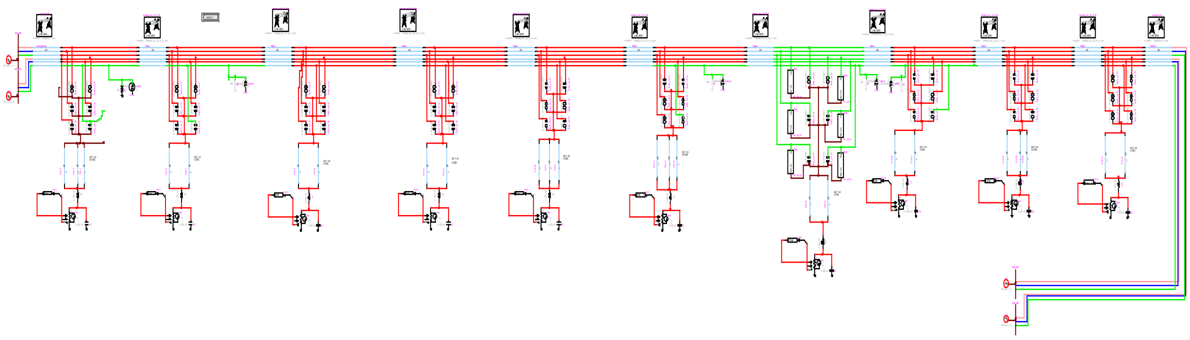


Figure 11. EMTP modelling of a 35 kV double line section

3. RESULTS AND DISCUSSION

The impact of the grounding impedance, the surge arrester density and the shield wire are analyzed in this section in order to propose the optimal solution for the 35 kV line in Vietnam. Calculation scenarios include:

– Base case as existing solution: no shield wire, RC1 grounding electrode (1 rod) at each tower, 1 set of surge arrester at tower 7. The interval of surge arrester installation is 6 spans. The configuation of the line is presented in Figure 12.

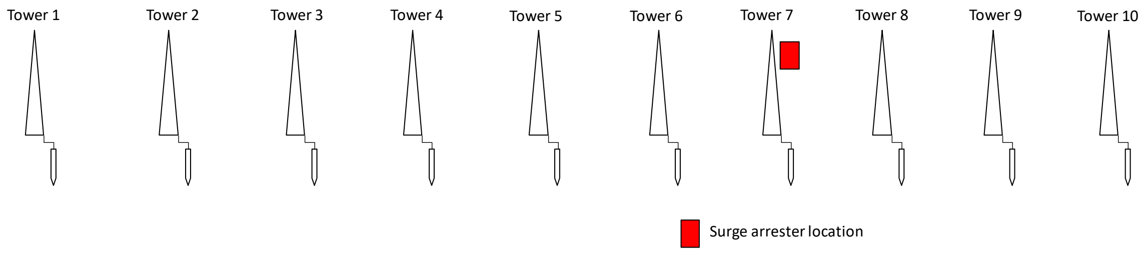


Figure 12. Lightning protection system of the existing solution

– Solution 1: no shield wire, RC2 grounding electrode (2 rods) at each tower within surger arrester, 1 set of surge arrester at each 3 spans.
– Solution 2: no shield wire, RC2 grounding electrode (2 rods) at each tower within surger arrester, 1 set of surge arrester at each 2 spans.
– Solution 3: installation of shield wire, shield wire is grounded at each 3 spans, RC1 grounding electrode (1 rod) at each tower, no surge arrester.
– Solution 4: installation of shield wire, shield wire is grounded at each 2 spans, RC1 grounding electrode (1 rod) at each tower, no surge arrester.
– Solution 5: installation of shield wire, shield wire is grounded at each tower, RC1 grounding electrode (1 rod) at each tower, no surge arrester.
– Solution 6: installation of shield wire, shield wire is grounded at each tower, RC2 (2 rods for the grounding electrode) at each tower within surger arrester, 1 set of surge arrester at each 3 spans. The configuation of the line is presented in Figure 13.

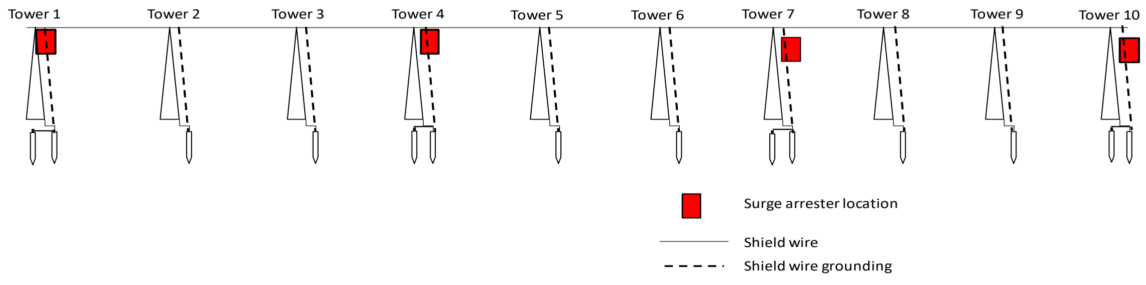


Figure 13. Lightning protection system of the solution 6

3.1. Influence of the grounding impedance and surge arrester density

The first group of solutions is based on the improvement of grounding structure and surge arrester density. A RC2 (2 rods) grounding structure is proposed to apply at each pole position within surge arrester installation. The value of the critical flashover currents is reported in Figure 14 for the base case and the proposed solution 1 and solution 2.

It should be noted that the critical flashover current in the base case is relatively low, less than 5 kA except the tower 7 with the installation of a set of surge arrester at this position. In case of the solution 1, the critical flashover current achieves 35kA by decreasing the spacing of surge arrester from 6 (equivalent to 400m) to 3 tower spans (equivalent to 200m) and reducing the grounding impedance of the tower within surge arrester. In case of the solution 2, the critical flashover current also achives 35kA at towers within surge arrester. It should be noted that higher number of protected tower can be obtained while decreasing the spacing of surge arrester to 2 spans (equivalent to 150m). Furthermore, we find that the surge arrester also improves the critical flashover current of the adjacent towers. The obtained results are similar to the finding of Ref [9], which proposed to install the surge arrester for each 200m across the distribution lines. The effectiveness of the lightning protection with a shorter surge arresters spacing can be explained by adding more evacuating path for the lines when be hit by a direct stroke. A reduced grounding impedance also helps to efficiently evacuate the lightning current and reduce the overvoltage on the insulator [22]. Therefore, a higher density of surge arrester and reduced grounding impedance are appropriate to slightly improve the lightning performance. However, the towers without surge arrester are still not protected and become the weakness of the line.

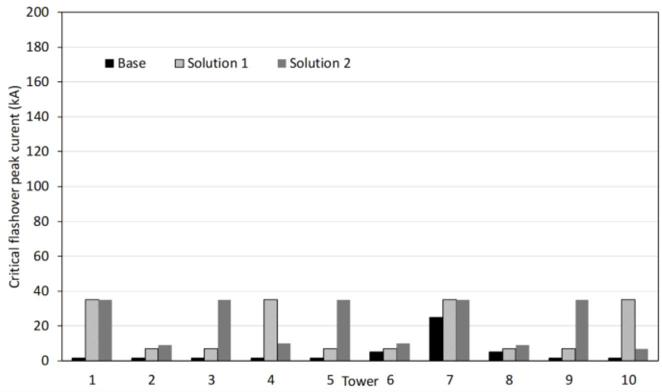


Figure 14. Critical flashover current for the base case, the solution 1 and solution 2

3.2. Influence of the periodical grounding of shield wires

As mentioned above, towers without surge arrester are not protected and become the weakness of the distribution lines. From this point of view, a shield wire was added with different grounding spacings to protect the line against direct strokes as proposed solution 3, 4, 5. The critical flashover current value of these solutions are compared to the base case and presented in Figure 15.

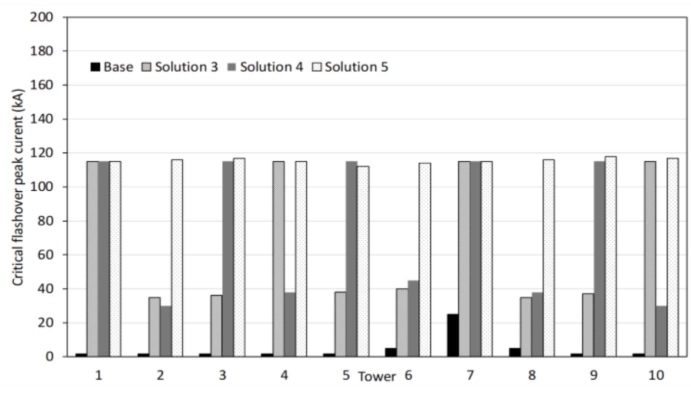


Figure 15. Critical flashover current for the base solution and the solution 3, 4 and 5

It is clearly showed that the installation of a shield wire significantly increases the critical flashover current in comparison to the base case. The critical flashover current can achive 115kA when the shield wire is grounded at the associated tower. The installation of the shield wire also helps to improve the lightning performance of the adjacent towers in comparison to the base case. It should be noted that the grounding interval of the shield wire has an effect on lightning performance where the best protection obtains with the grounding of the shield wire at every tower. This could be explained by the coupling between the shield wire and the conductor that leads to less overvoltage stress on the insulator and the various grounding points helps the lightning current efficently flowing to the earth [23], [24].

3.3. Combined effect of the shield wire and surge arrester

The solution 6 proposes a combination of surge arrester installed each 3 spans in addition to the shield wire in order to protect the line against the direct strokes to the conductors. The critical flashover current of this solution is presented in Figure 16.

It can be seen that the highest critical flashover currents achive around 150kA when both shield wire and surge arrester are used. This enhencement is due to the decrease of the insulator voltage caused by the branching effect of the shield wire on the lightning current and a narrow installing interval of the surge arrester [25]. From this result, it can be seen that the installation of both the shield wire and surge arrester is the complete solution for improving the lightning performance of the MV lines in Vietnam.

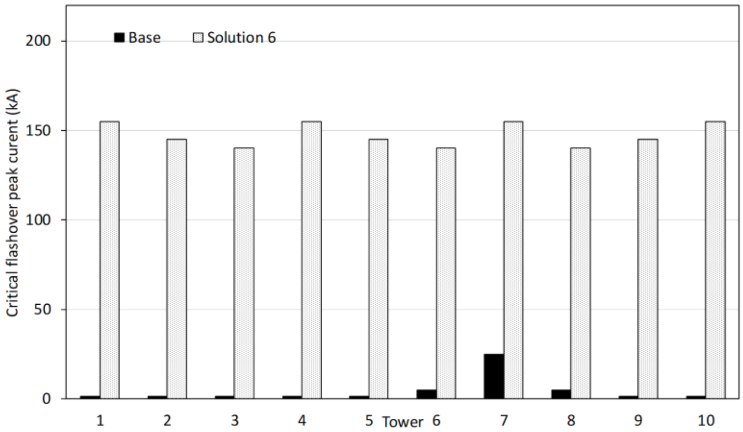


Figure 16. Critical flashover current for the solution 6

4. CONCLUSION

In Vietnam, 35 kV distribution lines, without shield wire installation and having a low density of surge arrester, often have a high flashover rate due to lightning activities. This article introduces a procedure calculation to improve the lightning protection performance of these lines by using both shield wire and surge arresters at narrow interval. The special point in this study is to consider the transient response of the ground electrode at high frequencies by using the finite element method which allows achieving more accurate estimation of lightning overvoltage.

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