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Evaluation of Technical Consequences of Line Arresters instead of Shield Wires on HV Overhead Transmission Lines

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***Abstract*— Ensuring the reliability of overhead transmission lines and reducing outages is of utmost importance in the power industry. Lightning strikes and back flash-over incidents are significant contributors to disruptions in service. While shield wires have traditionally been used to mitigate the impact of lightning, they have limitations, particularly in high-risk areas or specific tower configurations. Some experts advocate for the use of line surge arresters as a more effective solution. this study delves into the application of line surge arresters to enhance the reliability and performance of overhead transmission lines in the face of lightning strikes and other electrical disturbances. Line surge arresters are engineered to redirect excess voltage away from the transmission lines, thereby decreasing the likelihood of damage from lightning strikes. by incorporating these devices, utilities can bolster the resilience of their infrastructure and reduce downtime resulting from electrical disturbances. this proactive approach not only leads to cost savings but also elevates customer satisfaction. the utilization of EMTP and DIgSILENT software has been instrumental in conducting simulations for this study.**

Keywords— Line Surge Arrestors, Shield wires, Lightning strikes, Back flash-over, Insulator strings, Short circuit.

I. INTRODUCTION

One of the important issues that should be considered in the design of overhead power transmission lines is to protect the transmission lines against lightning strikes and back-flashovers, which can be occurred both directly and indirectly. In the first case, the lightning strikes directly to the phase conductor, and the generated overvoltage causes electrical discharge from the phase conductor to the tower. In the indirect case, lightning strikes the tower and, in case of high ground resistance, it causes electrical discharge between the tower and the phase conductor [1]. One of the oldest methods of protecting overhead transmission lines, especially against lightning strikes, is using shield wires (guard wires). Depending on the area and transmission corridor and the transmission line configuration, one or two-guard wires are used to protect the phase conductors. The general process of calculating the coverage angle and the protected area is mentioned in [2].

Suppose the protection angle is not large enough to cover the conductor at lower position. In that case, the lightning strikes directly at the phase conductor, generating an overvoltage that can cause a flash-over on the insulator strings. In addition, even if the coverage angle is appropriate, lightning can strike directly at the tower. If the resistance of the tower's ground system is high, the voltage at the top of the tower may reach to its critical level and causing a return indirect back flashover the insulator. By repeating this condition, the insulator strings will suffer from premature wear. Also shield wire connect towers together so for measuring ground resistance first we should open the shield wires or using high frequency measuring device. One of the suggested ways to solve back-flashover issue is to use the line arresters. Using Line surge arrester can be the one of the most effective methods to solve the lightning problems that can improve transmission system reliability[3]. This device acts generally as a non-linear resistor so that at operational voltage of transmission line, the very weak current passes throw the line arrester and it is normally limited to microampere values, but with increasing voltage of phase conductor, the current passing through it also increases to a maximum level according to line arrester class. Transmitting current to the ground system by line arrester reduces overvoltage and the power circuit can return to normal condition. If lightning strikes the tower directly, the overvoltage created in the tower due to the high resistance of the ground system may be transferred to the phase conductor via the line surge arrester and will be discharged in the adjacent towers with less ground resistance.

In [4] and [5] have studied various methods of lightning protection as shown on Table 1, to improve the efficiency of the overhead transmission line against lightning strokes, and among the proposed methods, the method of using a line surge arrester has been proposed as an economical method too.

Table head I. Comparison of different types of methods for lightning protection[4, 5]

Method of lightning protection	Feasibility check	Economic viability
Add or extend shielding wire(s)	-Lines are generally unshielded for specific reasons (river crossings/clearance issues) -Strongly depends on line design/parameters -Not effective for high footing resistance and bad soil resistivity	-High material & labor costs -Power interruption is required -Non-economical solution
Increasing BIL(Basic *Insulation* Level) by insulator extension or replacement	-Strongly depends on tower design and system clearances -Leads to traveling / propagating waves on the line for high footing resistances!	-High material & labor costs -Power interruption might be required -Non-economical solution -Experience required for insulators replacement in live conditions
Improve tower footing resistances	-Additional copper counterpoises and grounding extension might be completely inefficient with high soil resistivity -Only efficient for shielded lines -Eliminates only back flash-overs and doesn't influence shielding failures.	-Moderate installation costs -Improvement & cost efficiency is not guaranteed
Install Line Surge Arresters	-Versatile & Large feasibility -Highest protective effectiveness even for high footing resistances in all terrains -Eliminate all types of lightning failures.	-Low material & labor costs -Several options for live-line installation. -Cost-efficient solution. -Possibility to replace insulators and EGLA **(Externally Gapped Line Arresters)** as an integrated solution!

In [6] has been suggested that the guard wire can be removed, but the line surge arrester should be installed on all phases in the transmission line (connected between conductors and towers). This method naturally provides more reliability than the case where the guard wire is used. However, due to the structure of the overhead transmission line, The cost of installing surge arresters in the designated area, as well as obtaining the Right of Way (ROW) for the construction of overhead transmission lines in the country, may be slightly higher than usual.

Regarding to reduce the lighting arrester installing costs, in [7] the study on the determination of effective surge arrester locations in overhead transmission lines has yielded significant results. The analysis focused on the impact of lightning strokes on these lines, both with and without existing surge arresters.

Additionally, the study investigated the accurate representation of electrical equipment, such as transmission lines, tower footing resistance, insulators, and surge arresters, in determining over voltages caused by lightning strikes. This research has provided valuable insights into optimizing surge arrester placement and enhancing the protection of transmission lines against over voltages.

In this paper, according to the calculations and simulations presented in the next sections, it is suggested that the line surge arrester can be used only in the upper phase of the overhead transmission line to improve its lightning protection. Then, in section 3, the line's efficiency against lightning is examined. In section 4, the performance of the surge arrester in the event of a short circuit fault, and in section 5, the difference in tower weight and the amount of economic savings in the proposed model are investigated.

II. LIGHTNING EFFICIENCE OF WSW & NSW STRUCTURE

The EGM (Electro-Geometric Model) structure of double circuits tower with shield wire (WSW) and tower without shield wire (NSW) is examined to evaluate their performance due to lightning strokes. The coordination of each conductor and shield wire are which has been shown in Fig. 1 mentioned from top to the bottom in Table II.

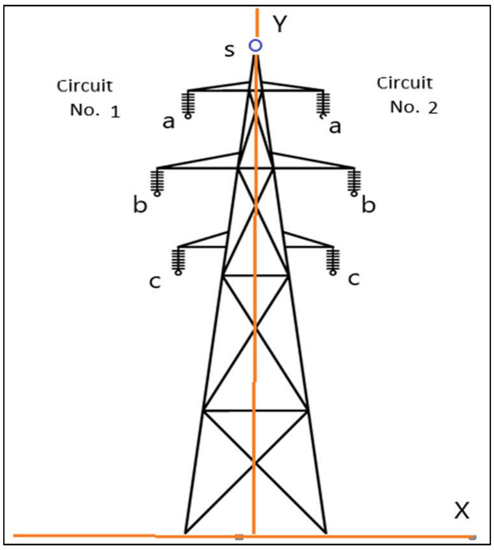

Figure 1. Structure Of Transmission Line Tower Used For Case Study

Table head II. Coordination of phases conductors and shield wire

Circuit No.	X_s	X_a	X_b	X_c	Y_s	Y_a	Y_b	Y_c
1	0	4.8	7	5.5	38.6	34.8	28.45	22
2	0	-4.8	-7	-5.5	38.6	34.8	28.45	22
Length Dimension is in meter(m)								

To analyze shield wire and conductor performance, the protected area with each of them should be calculated. In this regard, the conductor gap D_c (which shows the area where may lightning passed the shield wire and shielding failure occurred) and the protective gap D_g (which shows guard wire protected area), are respectively calculated by using (1) and (2) [8].

$$D_c = r_c[cos\theta - \cos(\alpha + \beta)] \quad (1)$$

$$D_g = r_c[\cos(\alpha - \beta)] \quad (2)$$

Where, the expression parameters have been shown in Fig.2.

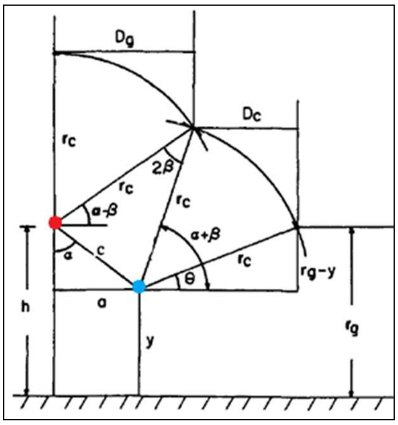

Figure 2. General structure and strike distances

When the guard wire is used for protection, this conductor is considered the protector against of the lightning strike, but when there is no guard wire, the first conductor at the highest point can be regarded as the lightning protective wire for the middle and lower phases. The formulas provided by[9] have been used to calculate the lightning strike distances r_c and r_g for this overhead transmission line as presented by (3).

$$\begin{cases} r_c = 10 * I^{0.65} \\ r_g = \begin{cases} [3.6 + 1.7 * \ln(43 - \bar{y})] * I^{0.6} & \bar{y} < 40m \\ 5.51 * I^{0.65} & \bar{y} \geq 40m \end{cases} \end{cases} \quad (3)$$

Where, the I is the amount of lightning current and the minimum value offered by [8], is 3kA, and $(\bar{y})$ is the average amount of conductor wire under protection minus 2/3 flash conductor wire as (4).

$$\bar{y} = y - \frac{2}{3} f \quad (4)$$

Using equation 3 and 4, the obtained values of D_g and D_c for 3kA lightning current are as Table III:

Table head III. Resultant D_c and D_g

Study Case	Conductor	D_c(m)	D_g(m)
With Shield Wire	First Phase	0	14.92
	Second phase	4.14	19.52
Without Shield Wire	Second Phase	1.35	20.14

The main difference between the D_g and D_c and D_c is that the lightning collected by protective conductor in D_g interval but if lightning hits the D_c interval, shielding failure may occur and can cause an over voltages in phases.

By increasing the lightning current, the r_c and r_g distance will increased. In some current the D_c interval will be zero, and it means the lightning current with high probability completely collected by protective conductor; this current is calculated by (5) and (6).

$$I = \left[\frac{r_{gm}}{10}\right]^{\frac{1}{0.65}} \quad (5)$$

Where

$$r_{gm} = \frac{\frac{h+y}{2}}{1 - \gamma sin\alpha} \quad (6)$$

Where r_{gm} is the value of r_g at I_m
h is protective conductor height,
y is height of a conductor, which is protected
γ is r_c/r_g , and α is shown in Fig. 2

The calculated maximum current is shown in Table 4, and related distances are stated in Table 5. (Canary and OPGW 12 conductor considered for phase and guard wire).

Table head IV. Resultant Dc and Dg

Case	Maximum current (kA)
Using exclusive wire as a shield wire	66.15
Using top phase conductor as a shield wire	14.40

Therefore, we have complete protection in the case of using phase conductor as guard wire in low current lightning. Calculation of the amplitude of parameters D_g and D_c based on the maximum strike's current gives the results presented in Table V.

Table head V. The protected distances

Case	Dg(m)	Dc(m)
Using exclusive wire as a shield wire	125.9	0
Using top phase conductor as a shield wire	54.45	0

In order to study the overvoltage due to lightning strike for two structures (with and without guard wire) the models in EMTP software are examined. It should be mentioned that in case of without guard wire one surge arresters are installed in all towers in the highest phase to limit over voltages due to lightning strikes. For presented structure tower and also according to the analytical calculations, the probability of lightning strikes in the second and third phases is very low, so the surge arresters are not considered for them.

A sample of arrester with the specifications of the following Table VI, has been used to simulate the electrical behavior of arresters. The voltage level of the simulated line is 230 kV, and the surge impedance of transmission line that calculated by EMTP software is 490 ohms. The simulated tower is also the same as Fig.1

Table head VI. Sample surge arrester.[10]

System Voltage(kV)	Ur(kV)	Uc (kV)	Class	30/60us		8/20us	
				1kA	2kA	5kA	10kA
245	198	158	3	382kV	400 kV	437 kV	465 kV

III. LIGHTNING STRIKES SIMULATION

For insulator modeling in transmission line a flash-over switch is used which its CFO is set according to the IEC 60077. CFO is the lightning critical flash-over voltage calculated for the line insulator, for transmission line model Frequency model base line is considered, and for tower model, a series RL circuit is considered. The value of related parameters are shown in Table VII, and the simulated circuits are shown in Fig.3, And 4.

Table head VII. Parameters Values Of Equivalent Circuit

Parameter	Value
Tower inductance	2.4uH
Tower resistance	4.59ohm
Critical flash over	1050kV
Source Voltage	230kV

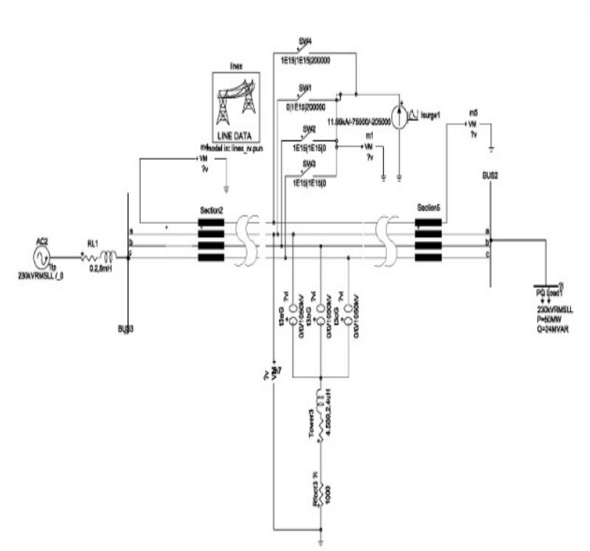

Figure 3. The simulated line with shield wire in EMTP

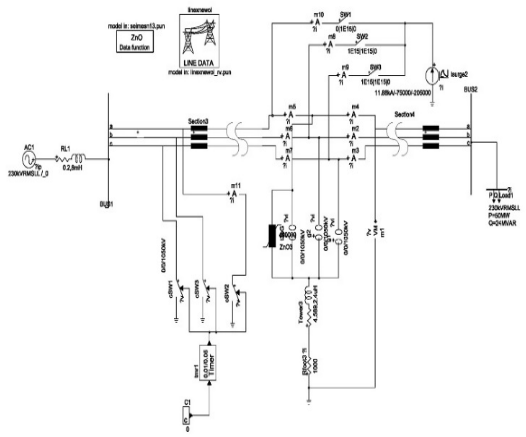

Figure 4. The simulated line with Line surge arrester in EMTP

For modeling of lightning strokes an impulse current with 4.3kA (The threshold current required to increase voltage based on surge impedance to reach the flashover value) amplitude (I_m=12, α=-75000 ,β=-205000), by mean of Cigre current source model, was injected into the first phase of the transmission line, and resulted over voltages is shown in Fig. 5. When there is shield wire (first case), it can be seen the over voltages amplitude is higher than second case (with line arrester). In first case the overvoltage amplitude can reach to critical value and flash over will be occurred on the insulator, but in 2nd case when the line arrester is connected between the conductor phase and tower, a large part of the Impulse current will be transferred to the ground system through the surge arrester and the overvoltage amplitude will strictly be limited arrester and so there won't be any flashover on the insulator.

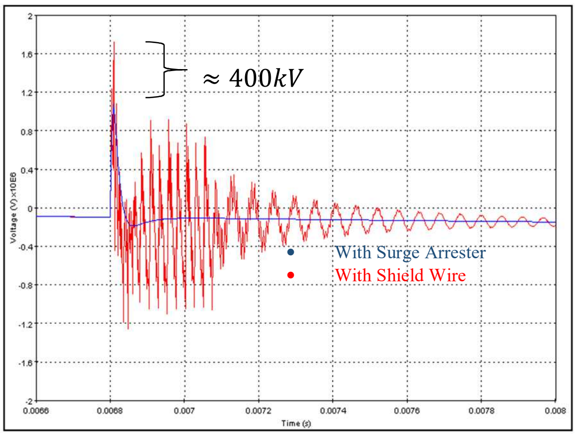

Figure 5. Over-voltage generated due to lightning struck over conductor phase

IV. SHORT CIRCUIT STUDIES

This section compares the two structures in terms of short-circuit current. To calculate the short circuit value, it is necessary to calculate the positive, negative, and zero sequence Impedance of the overhead transmission line considering two cases, as guard wire or, line surge arrester. In overhead transmission lines, + and - sequences impedances are equal, so only the one or + and zero sequences need to be calculated. To calculate the impedance value, the GMR and GMD values of the line conductors must first be used using (6) and (7) [11].

$$GMR = \sqrt[9]{(re^{-0.25})^3 d_{ab} d_{bc} d_{ac}} \quad (6)$$

$$GMD = \sqrt[3]{D_{ab} D_{ac} D_{bc}} \quad (7)$$

Where R is the outer radius of the conductor d is the distance between the conductors of the phases. D is equal to the distance between the phase conductors. After calculating the GMR and GMD values, the value of Z1will be calculated by the following equations:

$$z_1 = r_a + j(x_a + x_d) \quad (8)$$

$$x_a = 0.145 \log\left(\frac{1}{GMR}\right) \frac{ohm}{km} \quad at\ 50Hz \quad (9)$$

$$x_d = 0.145 \log(GMD) \frac{ohm}{km} \quad at\ 50Hz \quad (10)$$

Also, the value of Z0 can be determined using the following relations.

$$z_0 = z_1 + r_e + j(X_e - x_d) \quad (11)$$

Where $r_e = 0.142 \frac{ohm}{km}\ at\ 50Hz$,

$$X_e = 3 * 0.145 \log(D_e) \quad (12)$$

$$D_e = 691.2 \sqrt{\frac{\rho}{f}} \quad (13)$$

Where, P=soil resistivity (ohm.m), and F=frequency(Hz).

To obtain the short circuit current in 1 and 3 phase faults, the Digsilent software is used and The position of the conductors is entered in the software, and for the conductor of the transmission line, the Canary conductor is used, and for the wire guard, OPGW with a radius of 12 mm is considered the other electrical parameters are same as Table VII.

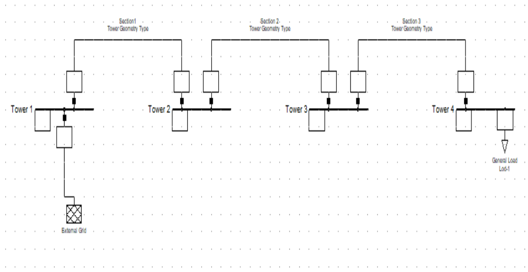

Figure 6. Single Line Diagram of under study network in Digsilent.

The simulated circuit is shown in Fig. 6. The amplitude of calculated impedance of Z1 and Z0 are presented in Table VIII.

Table head VIII. Amplitude of 1,2, and 0 sequence Impedance

No.	Case.	Ground Resistivity	Z_1	Z_0
1	With Shield Wire	10	0.0329+j0.214	0.22+j0.0.777
		100	0.0329+j0.214	0.273+j0.912
		1000	0.0329+j0.214	0.333+j1.052
2	Without Shield Wire	10	0.0329+j0.214	0.162+j0.856
		100	0.0329+j0.214	0.174+j1.058
		1000	0.0329+j0.214	0.178+j1.27

An investigation was conducted on a three-phase short circuit, which is a fault characterized by high amplitude of current, and a single-phase short circuit, which is a common fault in transmission lines. The simulation results are shown in Table IX.

Table head IX. Amplitude of Short circuit current in two O.H.T. line structures.

No	Case.	3 Phase Short Circuit (kA)	1 Phase Short Circuit (kA)
1	With Shield Wire	24.57	23.67
2	Without Shield Wire (using surge arrester)	24.57	22.97

In the three-phase short circuit fault, the values of short circuit in two O.H.T. line structures are the same, because the zero sequence impedance has no impact in this case, but in the case of single-phase short circuit fault to ground, the amount of short-circuit current decreases due to increasing in zero-sequence Impedance of the structure without guard wire. The results of two cases have been shown in the Fig. 7 to 9. respectively. By utilizing a lightning arrester to conduct surge current to the earth, the amplitude of the short circuit will be limited to a safe level. This is a significant advantage of employing a lightning arrester in the context of short circuit incidents.

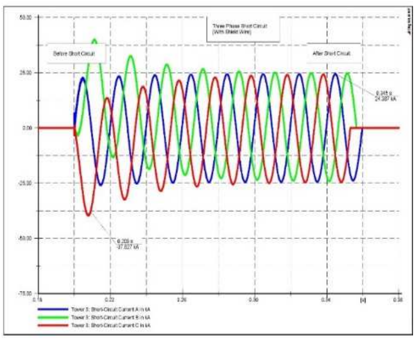

Figure 7. 3 Phase short circuit fault current(kA).

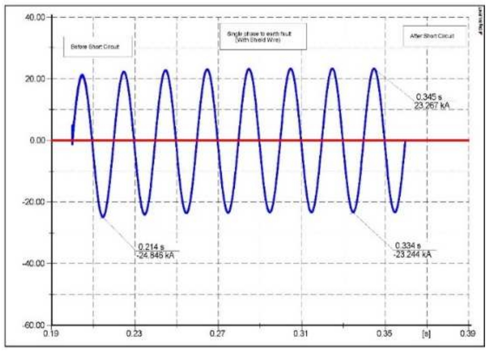

Figure 8. Single phase short circuit fault current(kA) in WSW.

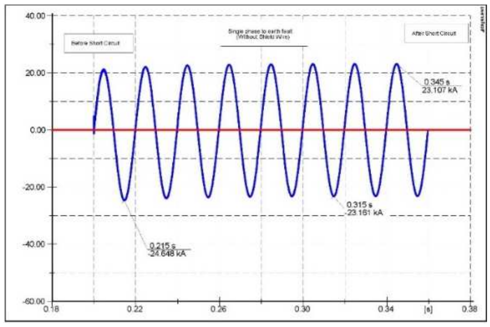

Figure 9. Single phase short circuit fault current(kA) in NSW.

V. Economical Assessment

Installing the lightning surge arrester reduces the power outage rate, which causes by lightning strikes, especially in areas with high ground resistivity-of transmission line outage can increase the reliability and continuous transfer energy which result in grow in income of regional electrical companies. By removing shield wire and supporting structure, tower become lighter and it reduces the iron consumption and it lets to save more money. In this regard the elements for economical cost analysis are as follows:

-Tower weight (kg)
-Iron costs per kilogram
-cost of guard wire/km

According to [8] and [13], the median current of lightning is 31kA. Based on this current and relation 5, the strike distance is calculated to be 93m. Considering a ground flash density of 5.5 (worst case in Iran) and an area of 27,171 m^2, (the area with radius of 93m)the number of flashes to the conductor can be determined by the following Expression:

$$N_s = \frac{GFD * A}{1000^2} \qquad (14)$$

- A ,represents the area of the protected area(By radius of 93m)
- GFD stands for ground flash density- The number of flashes that strike the conductor is the focus
- N_s flashes to the area

And So on:

$$SP = N_s * 0.001 \qquad (15)$$

- SP is Shield penetrate per year

So the struck lightning to the light arrester is calculated to be 7.45 per 50 years (representing the operational years of the OHT line). Considering an OHT line with 3 towers per 1 km (each tower being 300m), the probability of failure of the light arrester is too small. so the impact of light arrester price during the operation of overhead line is negligible.

Table X lists the values of each economical component of the investigated overhead transmission line. In the economic analysis, a transmission line with 1-kilo meter length and having 3 spans (based on our experience, the ruling spans for lattice towers are typically around 300 meters) and as well as 4 towers is taken into consideration. In the case of without guard wire, one surge arrester was implemented at upper phase conductor for each tower. Savings on 1 km of overhead transmission line are listed in Table XI. For this case, 3 towers were considered per km and 2 sample surge arresters per circuit per tower at a price of 2000 US dollar have been considered.

Table head X. Economic analysis of the overhead line parameters

Voltage(kV)	No. Of Shield Wire	Tower Weight with shield wire (kg)	Tower Weight without shield wire (kg)	Iron cost per kg	Shield wire cost per km
230	1	11647	11300	1$	475$

Table head XI. Calculated saved money per kilometer

Voltage	Saved money per km ($)	Cost of lightning surge arrester per km ($)
230kV	1516	12000

It is evident that, one part of the cost is reimbursed by saving the iron used in the tower. Additionally, increasing reliability increase income and it could compensate more cost.

VI. CONCLUSION

In this paper, the lightning effects on a typical high voltage overhead power transmission line is observed and its transient electrical behaviors due to lightning strokes and short circuit faults are simulated and also its economical aspect has been presented in two following modes of the lines with traditional tower structure such as 230kV double circuit (one guard wire) and 132kV single circuit (two guard wire) In order to assess financial savings across various voltage levels and tower structures, a comprehensive analysis is required. This analysis will provide valuable insights into potential cost reductions and efficiency improvements.:

1st mode; Considering guard wire(s) and not using line surge arrester

2nd mode; Using line surge arrester and eliminating the guard wire(s).

In point of view to minimize the effect of the lightning strokes, the obtained results can be classified as follows:

- The installed arresters structure had a better transient electrical performance than the traditional tower structures with 1 or 2 shield wires
- In short circuit fault studies, the results of the both mentioned structures are nearly the same.
- In structures of overhead transmission lines that are used line arresters, the required spaces for installing the insulators strings and the towers can be reduced and its structure cab be closed to compact towers.
- Due to the elimination of the guard wire, the towers can be isolated to each other's, so the measurement of the ground resistance of the towers can be simply done. It is possible to implement the old methods such as using the simple earth meter.

By implementing these measures, we can enhance the efficiency and resilience of our transmission infrastructure, ultimately leading to a more secure and sustainable energy system.

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