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Analysis of Lightning Arrester Installation Location on Transformer 1 Bungaran Substation

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ABSTRACT: Lightning arrester is a device used in substations to protect electrical equipment from voltage increases caused by solar circuits or lightning. The purpose of the study is to calculate the lighting arrester spark voltage and voltage rise on the transformer, and analyse the lightning arrester distance to the power transformer and protection factor. Surge voltages, due to disturbances such as lightning strikes, can be very high without lightning arresters, namely 305,065 kV at t = 10 µsec. With an arrester, the voltage is reduced to 262,726 kV from t = 9,05 µsec to 220,387 kV at t = 10 µsec, indicating effective protection. Without lightning arresters, the clamping voltage on the transformer can reach 340,442 kV at t = 12 µsec, exceeding the BIL (325 kV) and risking damage. With an arrester, the pinch voltage is dampened from 306,777 kV at t = 11,05 µsec to 273,169 kV at t = 12 µsec, keeping it below the BIL. The optimal distance of lightning arrester placement at Bungaran Substation is 6,6077 m, while the installed distance is 7 m. This distance complies with PT PLN's standard of up to 34 m for double-circuit transmission, ensuring effective protection. The lightning arrester provides good protection for the 30 MVA Power Transformer with a protection level of 288,998 kV and a protection factor of 11,0774%. This keeps the voltage below BIL (325 kV), effectively reducing the risk of damage from voltage surges.

KEYWORDS: Location, Installation, Ligtning, Arrester, Transformer

I. INTRODUCTION

The substation is one of the components in the power distribution system plays a very important role because it is the terminal to the service of electricity to consumers. The substation functions to receive and distribute electricity safely and reliably at a certain voltage, distributing power to other substations and distribution substations through medium voltage feeders [1-4].

Thus the substation has an important role in the distribution of electrical energy. Electrical energy is lineled without being affected by outside interference. One of the most common disturbances is lightning strikes. Lightning strikes at the substation will cause an increase in voltage on the equipment in the substation If this voltage exceeds the equipment insulation limit (BIL), it can damage the equipment insulation [1,5].

Transformers are one of the important components in the distribution of electrical energy which serves to increase or decrease the voltage as needed [1]. At Bungaran Substation, Transformer 1 with a capacity of 30 MVA and a voltage of 66/20 kV is one of the critical elements in the distribution of electrical energy. In order for transformer operations to remain reliable and safe, adequate protection against various disturbances is needed, one of which is interference due to lightning strikes.

Lightning strikes can cause very high voltage spikes (transients) in a short period of time, which can potentially damage electrical equipment, including transformers. Therefore, the installation of protection equipment such as lightning arresters is very important. Lightning arresters function to protect the transformer by lineling excess energy due to voltage surges directly to the ground, thus preventing damage to the transformer [6-7].

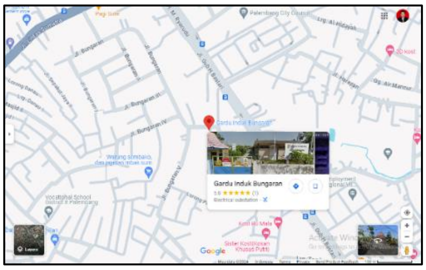
However, improper placement of lightning arresters can reduce the effectiveness of the protection provided. Therefore, analysing the placement of lightning arresters on transformers is very important to ensure that transformers are optimally protected [6-7]. Based on these problems, the purpose of this study is to analyse the placement of lightning arresters on Transformer 1 of Bungaran Substation. It is expected that the results of this study can provide appropriate recommendations regarding the placement of lightning arresters so as to improve the reliability and safety of transformer operations.

II. RESEARCH METHODS

A. *Time and Place of Research*

The research implementation started from 26 May 2024 to 29 June 2024. The research site is PT PLN (Persero) Sumatra Transmission Service Unit (UPT) Palembang Transmission Service Unit and Substation (ULTG)

Keramasan Bungaran Substation Palembang, which is located at 8 Ulu Village, Jakabaring District, Palembang City, South Sumatra Province 30267. The object of research is the lightning arrester at Transormator 1 Bungaran Substation.



Gambar 1. Lokasi penelitian

B. *Research Stages*

Lightning arresters are devices used in power systems to protect equipment from voltage surges caused by lightning strikes or other disturbances such as switching surges. The main function of a lightning arrester is to limit the surge voltage that can reach electrical equipment, by conducting the excess voltage to ground. Surges may propagate inside conductors during the following events [5-7]:

- Failure of the lightning protection angle, resulting in lightning surge flowing inside the phase conductor.
- Backflashover due to high grounding values, either at the substation or on the transmission line.
- CB/ DS switching process (surge).
- Phase-phase, or phase-ground faults either in transmission lines or in substations.

During a surge event, travelling waves propagate across the transmission system conductors at speeds close to the speed of light. Surges with wavelengths in the order of micro seconds are dangerous if the surge voltage value arriving at the equipment is higher than the Basic Insulation Level (BIL) of the equipment. For this reason, lightning arresters are installed to cut the surge voltage by conducting the surge current to the ground in a very short order, where the effect of the follow current is not neutralised. Lightning arresters have the following characteristics [5-7]:

- At operating voltage (rms) the lightning arrester is an insulator. The leakage current to ground is still present, but on the order of milli-Amperes. The majority of this leakage current is capacitive current.
- During a lightning surge, lightning arresters are conductive, with very low resistance values. Lightning arresters conduct surge currents to ground in the order of kilo-Amperes. The lightning arrester is immediately insulator after the surge has been successfully passed, thus eliminating the influence of the follow current.

The research began with site observation and collection of operational data on power transformers, lightning arresters, towers, and transmission lines. This data was analysed to calculate surge impedance, lightning arrester spark voltage, voltage rise at the power transformer, optimal lightning arrester spacing, breakdown voltage of the air insulator, and protection factor. The results of the calculations were analysed using the Lattice Diagram method to obtain the reflected and conducted waves at the transition point, and then compared with the SPLN 7:1978 standard [8].

1. *Maximum Voltage System*

The highest system voltage is taken as 110% of the nominal system voltage. The maximum voltage that an arrester terminal can receive is the voltage that can stop the aftershock current that occurs when there is a spark in the arrester. Determination of this voltage can also be used to determine the highest or maximum system voltage that can be generated by the substation. The highest system voltage can be determined using the following equation [9-11]:

$$V_m = 1{,}1 \times V_n \quad (1)$$

Description:

V_m = Maximum voltage system (kV)
V_n = Nominal voltage system (kV)
1,1 = System highest voltage tolerance 110%

2. *Arrester Rated Rating*

The rated voltage of the arrester is the most important feature to protect the substation. The working voltage of the arrester below the Basic Insulation Level (BIL) of the protected equipment indicates the protection level of the arrester. If the working voltage of the arrester is below the BIL of the protected equipment, optimum safety of the equipment can be obtained. The grounding coefficient is 0.8 (80% arrester), in accordance with the theoretical basis of the directly earthed system. The rated voltage of the system arrester can be determined using the equation as [10-11]:

$$V_c = V_m \times C_g \quad (2)$$

Description:

V_c = Arrester rated voltage (kV)
V_n = Nominal voltage of the system (kV)
C_g = Grounding coefficient (1 or 0,8)

3. *Surge Impedance*

For transmission line conductors that have sag, the height of the conductor from ground level can be calculated by reducing the height of the conductor on the cross arm by the amount of sag. The sag or bending distance between two transmission towers, depends on the weight and length of the conductor wire, and the resulting tensile strength. The amount of andongan can be calculated by the equation [3]:

$$D = \frac{WS^2}{8\,T} \quad (3)$$

Description:

D = Sag (m)
T = Horizontal tension of the conductor (kg)
W = Conductor weight per unit length (kg/m)
S = Length of line (m)

Surge impedance for air conductors is influenced by the height of the conductor above the ground and the radius of the conductor, so the average height of the conductor from above ground level needs to be determined first [3]:

$$h = \frac{(h_{upper} - D) + (h_{middle} - D) + (h_{bottom} - D)}{3} \quad (4)$$

Description:

h = Average height of conductor from above ground level (m)

h_{upper} = Height of upper cross arm from above ground level (m)

h_{middle} = Height of middle cross arm from above ground level (m)

h_{bottom} = Height of bottom cross arm from above ground level (m)

Surge impedance is the impedance value obtained during a surge, whether it is a lightning surge or a short circuit surge. Surge impedance is also influenced by the constants L and C that propagate on the conductor wire, where the two constants are also influenced by the characteristics of the wire. The surge impedance for air conductors is 400 Ω - 600 Ω. The surge impedance for air conductors is as follows [12]:

$$Z_1 = \sqrt{\frac{L}{C}} \quad (5)$$

If: $L = 2 \times 10^{-7} \, ln\left(\frac{2h}{r}\right)$ (6)

$$C = \frac{1}{18 \times 10^9 \, ln\left(\frac{2h}{r}\right)} \quad (7)$$

Then: $Z_1 = \sqrt{\frac{2 \times 10^{-7} \, ln\left(\frac{2h}{r}\right)}{\frac{1}{18 \times 10^9 \, ln\left(\frac{2h}{r}\right)}}}$

$$= \sqrt{36 \times 10^2 \left(ln\left(\frac{2h}{r}\right)\right)^2} = 60 \, ln\left(\frac{2h}{r}\right) \quad (8)$$

While the surge impedance for cables is influenced by the radius of the cable wrapping insulation, the radius of the conductor, and the permittivity of the cable, namely [12]:

$$Z_C = \left(\frac{60}{\epsilon}\right) ln\left(\frac{R}{r}\right) \quad (9)$$

The surge impedance for cables is 20 Ω - 60 Ω [12].

Description:

Z_1 = Surge impedance for air conductor (Ω)

r = Conductor radius (m)

L = Inductance of the conductor (H/m)

C = Conductor capacitance (F/m)

Z_C = Surge impedance for cable (Ω)

R = Cable wrap insulation radius (m)

ϵ = Relative permittivity of cable insulation (F/m)

4. *Propagation Speed of Surge Wave*

A wave propagating with constant L and C along a wire, makes the voltage and current waves propagate with the same speed. In addition, the propagation speed of the wave is also affected by a proportional factor, namely the characteristics of the wire travelled. The wave propagation speed for an air wire is as follows [12-14]:

$$v = \frac{1}{\sqrt{LC}} \quad (10)$$

Description:

v = Speed of propagation of surge wave (m/μdetik)

5. *Lightning Arrester Spark Voltage*

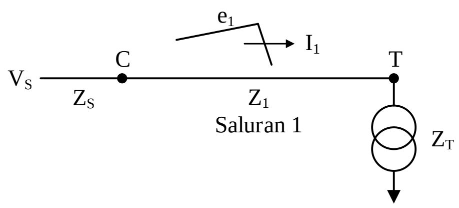


Figure 2. Simple one-line circuit [12]

The repetitive reflection method commonly embodied in the form of a ladder diagram is a suitable way to observe the reflection trace of a surge wave travelling on a line, the horizontal axis to name the reflection line on the line and the vertical axis to name the time increment of the total time it takes for the surge wave to traverse the line in one direction: S/v. From this diagram, the value of the total surge voltage on the line at each point and time can be obtained. The use of this method can be further explained in the determination of surge voltage and surge current for the circuit form shown in Figure 2 [12-14].

Point C and point T in Figure 2 indicate a relationship of two different values of resistance or surge impedance, line-1 with surge impedance (Z_1) has a total length from point C to point T equal to S. By considering Z_S as the source side surge impedance and Z_T as the load side surge impedance. If the surge voltage from the source side (V_S) is applied to line-1, the surge voltage wave (e_1) and surge current (e_1) will appear on the line, propagating from point C to point T [12].

A surge wave that arrives at a point connecting two different surge impedances (transition point) will cause a reflected surge wave at this point. The incident surge wave ($e_1$dan i_1) in line-1 will cause a reflected surge wave at point T after it arrives at the point at time t. And then this reflected surge wave will propagate and arrive at point C at time $2t$ and cause a new reflected surge wave at point C, this new reflected surge wave will again propagate towards point T and cause a new reflected surge wave again after arriving at point T at time $3t$. At each time, the total surge voltage or surge current at each point of the line is the sum of the values of all surge voltage or surge current waves arising on the line at that point and time. Time (t) is the time it takes for the surge wave to propagate on line-1 from point C to point T or vice versa, if the speed of surge wave propagation is v and the length of the line is S then time (t) is [12]:

$$t = \frac{S}{v} \quad (11)$$

Description:

t = Time (seconds)

Figure 2 shows the solar lightning wave coming from the left and after the wave reaches the lightning arrester installation point, part of the wave will be reflected and part of the wave will be forwarded. To determine the spark voltage of the lightning arrester, the reflection and forwarding operators must first be determined [12-14].

$$a = \frac{Z_C - Z_1}{Z_C + Z_1} \quad (12)$$

$$b = \frac{Z_1 - Z_C}{Z_1 + Z_C} \quad (13)$$

$$a' = \frac{2Z_C}{Z_C + Z_1} \quad (14)$$

$$b' = \frac{2Z_1}{Z_1 + Z_C} \quad (15)$$

Description:

a = Reflection operator for waves coming from the left

b = Reflection operator for waves coming from the right

a' = Forward operator for waves coming from the left

b' = Forward operator for waves coming from the right

For the steepness of the first incident wave, the steepness time of the wave entering the substation or transformer must be determined, and it is assumed that the steepness time of the wave (t) is every 2 µsec and the lightning surge (A) of 1,000 kV, and the damping factor (α) is $A \times a'$. If [12-14]:

i = 0, 2, 4,..... n is the index of the wave steepness time every 2 µsec. Suppose: i = 2, 6, 10,..... n is the index of the steepness time of the incident wave, and i = 4, 8, 12,..... n is the index of the steepness time of the reflected wave.

j = 1 , 3, 5,..... n is the index of the damping factor

The voltage value at the aerial wire cable connection point starts at $t = 0$, and the voltage value at the next time is the sum of the previous voltage value and the damping factor. The voltage value of the reflected wave is the same as that of the incident wave. Therefore, the voltage at the aerial wire-cable connection point when the lightning arrester is not present for every 2 µsec is [12]:

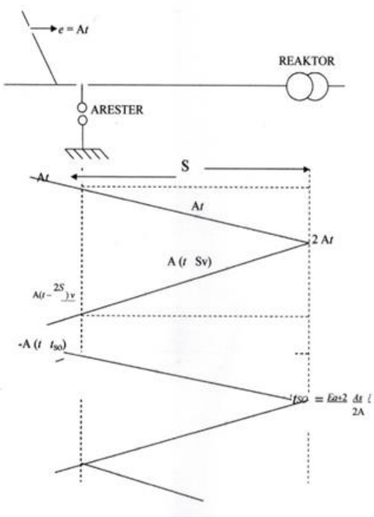


Figure 3. Lattice Diagram between the lightning arrester and the reactor [12]

$t = 0$ µsec; $e_{t=0} = 0$

$t = 2$ µsec; $e_{t=2} = e_{t=0} + \frac{\alpha^1}{10^0}$

$t = 4$ µsec; $e_{t=4} = e_{t=2}$

$t = 6$ µsec; $e_{t=6} = e_{t=4} + \frac{\alpha^1}{10^0} + \frac{\alpha^3}{10^4}$

$t = 8$ µsec; $e_{t=8} = e_{t=6}$

$t = 10$ µsec; $e_{t=10} = e_{t=8} + \frac{\alpha^3}{10^4} + \frac{\alpha^5}{10^8}$

$t = 12$ µsec; $e_{t=12} = e_{t=10}$

Then the spark time of the lightning arrester (t_{S0}) at the location of the arrester installation can be determined using the following equation [12]:

$$t_{so} = 8 + \Delta t \quad (16)$$

Description:

t_{so} = Spark over time for surge arrester (µsec)

8 = Time at time 8 µsec

Δt = The voltage time based on the surge arrester initial time gelombang (µsec)

While the voltage time based on the lightning arrester wavefront time (Δt) can be determined using the following equation [12]:

$$E_a = e_{t=8} + b'\left(\frac{\alpha^3/10^4}{2}\right)\Delta t$$

$$\Delta t = (E_a - e_{t=8})/b'\left(\frac{\alpha^3/10^4}{2}\right) \quad (17)$$

Description:

E_a = Basic insulation level of surge arrester (kV)

$e_{t=8}$ = Voltage at the terminal point at time 8 µsec

Furthermore, the discharge voltage or working voltage can be determined $\left(e_{t=t_{S0}}\right)$ of the lightning arrester. The working voltage or discharge voltage is one of the factors that determine the level of protection of the lightning arrester. If the working voltage of the lightning arrester is below the BIL of the protected equipment, then a safety factor sufficient for optimum equipment protection can be obtained. The discharge voltage/working voltage of the lightning arrester can be determined using the following equation [12]:

$$e_{t=8+\Delta t} = e_{t=8} + \left(\frac{e_{t=10} - e_{t=8}}{2}\right)\Delta t \quad (18)$$

$$e_{t=10} = e_{t=8+\Delta t} - \left(\frac{e_{t=10} - e_{t=8}}{2}\right)(2\mu t - \Delta t) \quad (19)$$

6. *Determination of Maximum Distance for Arresters and Power Transformers*

The voltage rise in the transformer is the voltage that arises when a surge occurs. If the voltage arising is below the basic insulation level of the transformer, the transformer can be protected. The voltage rise on the transformer can be determined using the equation [12-14]:

$t = 0$ µsec; $e_{t=0} = 0$

$t = 2$ μsec; $e_{t=2} = 0$

$t = 4$ μsec; $e_{t=4} = e_{t=2} + \frac{2\alpha^1}{10^0}$

$t = 6$ μsec; $e_{t=6} = e_{t=4}$

$t = 8$ μsec; $e_{t=8} = e_{t=6} + \frac{2\alpha^3}{10^4}$

$t = 10$ μsec; $e_{t=10} = e_{t=8}$

$t = 10 + \Delta t$ μsec; $e_{t=10+\Delta t} = e_{t=10} + \left(\frac{\frac{2\alpha^1}{10^0} + \frac{2\alpha^3}{10^4} + \frac{2\alpha^5}{10^8} - e_{t=10}}{2}\right)\Delta t$

$t = 12$ μsec;

$$e_{t=12} = e_{t=10+\Delta t} - \left(\frac{\frac{2\alpha^1}{10^0} + \frac{2\alpha^3}{10^4} + \frac{2\alpha^5}{10^8} - e_{t=10}}{2}\right)(2\mu t - \Delta t)$$

$t = 14$ μsec; $e_{t=14} = e_{t=12}$

7. *Distance of Lightning Arrester to Power Transformer*

Although it is best to place the *arrester* as close as possible to the protected appliance, in practice this is sometimes not possible if the distance is too great. The abnormal voltage arriving at the terminals of the equipment will be higher than the discharge and arrester voltages. The relationship between the terminal voltage of the protected appliance and the distance from the *arrester* is as follows [12-14]:

$$E_p = E_a + 2\frac{A\,S}{v}$$

$$S = \left(E_p - E_a\right)\frac{v}{2A} \quad (20)$$

Description:

E_a = Basic insulation level of surge arrester (kV)

E_p = Increasing voltage on the transformer (kV)

A = $\frac{de}{dt}$ = the steepness of the surge wave (kV)

S = Protective distance between surge arrester and transformer (m)

8. *Insulator Breakdown Voltage in Air*

The amount of voltage arising on the transmission insulator depends on the two lightning parameters, namely the peak and steepness of the lightning wavefront. Not all lightning strikes can cause a fire jump on the insulator because it also depends on the amount of voltage that arises and does not exceed the breakdown voltage on the insulator ($E_{50\%}$) [12-14].

$$E_{50\%} = \left(K_1 + \frac{K_2}{\Delta t^{0,75}}\right) \times 10^3 \quad (21)$$

Description:

$E_{50\%}$ = Breakdown voltage of insulator (kV)

K_1 = 0,4 × Insulator span length (m)

K_2 = 0,71 × Insulator span length (m)

Δt = Sparkover time (μsec)

9. *Nominal Discharge Current*

The nominal discharge current is the current with a certain peak price and waveform that is used to determine the class of the arrester according to its current capability and protective characteristics. For the discharge current in a travelling wave event it can be determined using the following equation [12-14]:

$$I_a = \frac{2E_{50\%} - E_a}{Z_1} \quad (22)$$

Description:

I_a = Arrester discharge current (kA)

10. *Protection Factor of Surge Arrester*

The protection factor is the voltage difference between the BIL of the protected equipment and the working voltage of the arrester. When determining the level of protection for equipment protected by an arrester, a price is generally taken that is 10% above the working voltage of the arrester, the aim is to overcome the increase in voltage on the connecting wire and factory tolerance. This protection factor is generally 20% of the equipment BIL for arresters installed near the protected equipment. Protection Factor (FP) can be determined using the following equation [12-14]:

$$FP(\%) = \frac{BIL - Protection\ Level\ of\ Surge\ Arrester}{TID} \times 100\% \quad (23)$$

Description:

$Protection\ Level\ of\ Surge\ Arrester = E_a + 10\%$ (wire length + factory tolerance)

III. RESULTS AND DISCUSSION

A. *Research Data*

1. *Transformer Data*

Figure 4. Transormator 1 Bungaran Substation

- Transformer capacity : 30 MVA
- Frequency : 50 Hz
- Primary voltage : 66 kV
- Secondary voltage : 20 kV
- Year of manufacture : 2013
- Type : SFZ-20000/70
- Serial number : 3011120024
- Standard : IEC 60076
- Phases : 3 (three)
- Impedance : 12,93 %
- BIL : 325 kV

- Brand : PAUWELS

2. Lightning Arrester Data

Figure 5. Lighting Arrester on Transormator 1 Bungaran Substation

- Brand : ABB
- Type : PEXLIM
- Nominal voltage : 70 kV
- Rated voltage : 75 kV
- BIL (E_a) : 270 kV
- Nominal discharge current : 10 kA
- Serial number : R = 75228567, S = 75228666, T = 75228565
- Frequency : 50 Hz
- Installation distance : 7 m

3. Transmission Line Conductor Data

Figure 6. Transmission line

- Conduit wire type : T- ACSR
- Nominal size : 120 (mm^2)
- Cross-sectional area : Al : 124,7 mm^2, St : 29,10 mm^2
- Diameter (d) : 16,1 mm = 0,0161 m
- Radius (r) : 8,05 mm = 0,00805 m
- Weight (W) : 532,9 kg/km = 0,5329 kg/m
- Minimum tensile strength (T) : 5.540 kg
- Insulator stretch length : 0,886 m

4. Transmission Tower Data

- h : 32,2 m
- h_{upper} : 28,1 m
- h_{middle} : 23,8 m
- h_{bottom} : 19,5 m
- S : 218 m

B. Results

1. Maximum Voltage System

The highest voltage of the system is taken from the price of 110% of the normal voltage of the system. This voltage determination can also be used to determine the highest or maximum system voltage that can be generated by the Bungaran Substation. To calculate the highest voltage of the system using equation (1):

$$V_m = 1{,}1 \times V_n$$
$$= 1{,}1 \times 66 = 72{,}6\ kV$$

2. Arrester Rated Rating

Determination of the rated *arrester* rating or the basic voltage of *the arrester* can be determined based on the maximum system voltage that may occur. To determine the magnitude of the basic voltage of the *arrester* or the rated voltage of *the arrester*, equation (2) can be used as follows:

$$V_c = V_m \times C_g$$
$$= 72{,}6 \times 0{,}8 = 58{,}08\ kV$$

3. Surge Impedance

Sag is the bending distance of a stretch of conductor wire between two transmission towers which is calculated based on the straight line (horizontal) of the two towers. The value of the transmission conductor can be determined using equation (3) as follows:

$$D = \frac{W\,S^2}{8\,T}$$
$$= \frac{0{,}5329 \times 218^2}{8\,(5.540)} = \frac{25.326}{44.320} = 0{,}5714\ m$$

To determine the surge impedance, it must first be determined the average height of the conductor from above ground level, using equation (4), namely:

$$h = \frac{(h_{upper} - D) + (h_{middle} - D) + (h_{bottom} - D)}{3}$$
$$= \frac{(28{,}1 - 0{,}5714) + (23{,}8 - 0{,}5714) + (19{,}5 - 0{,}5714)}{3}$$
$$= \frac{(27{,}5286) + (23{,}2286) + (18{,}9286)}{3} = \frac{69{,}6858}{3} = 23{,}2286\ m$$

After obtaining the average height of the conductor from above ground level, the surge impedance for the air conductor using equation (8):

$$Z_1 = 60\ ln\left(\frac{2h}{r}\right)$$
$$= 60\ ln\left(\frac{2 \times 23{,}2286}{0{,}00805}\right)$$
$$= 60 \times 8{,}6606136 = 519{,}6368\ \Omega$$

Meanwhile, the surge impedance for cables is $Z_1 = 22\ \Omega$

4. *Propagation Speed of Surge Wave*

The propagation speed of surge wave on a transmission line can be determined using equation (10) as follows:

$$v = \frac{1}{\sqrt{L\,C}}$$

$$= \frac{1}{\sqrt{\left(\frac{2 \times 10^{-7}\, ln\left(\frac{2h}{r}\right)}{18 \times 10^{9}\, ln\left(\frac{2h}{r}\right)}\right)}} = \frac{1}{\sqrt{\frac{2 \times 10^{-7}}{18 \times 10^{9}}}} = \frac{1}{\sqrt{\frac{1}{9} \times 10^{-16}}} = \frac{1}{\frac{1}{3} \times 10^{-8}}$$

$$= 3 \times 10^{8}\,\frac{m}{detik} = \frac{3 \times 10^{8}\, m}{10^{6}\, \mu detik} = 300\; m/\mu detik$$

5. *Lightning Arrester Spark Voltage*

Figure 7 shows the lightning surge wave coming from the left and after the wave reaches the lightning arrester installation point, part of the wave will be reflected and part of the wave will be forwarded. To determine the lighting arrester spark voltage, the reflection and forwarding operators must first be determined.

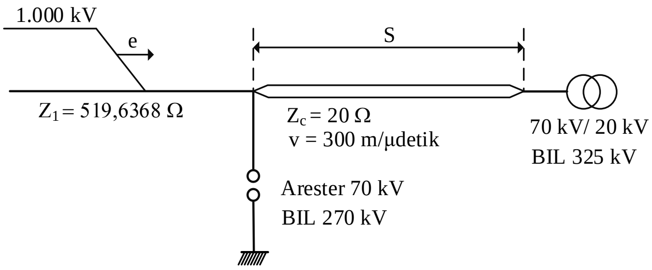


Figure 7. Transormator and lightning arrester separated by a distance of S

The bounce and forward operators can be determined using equations (12) to (15) as follows:

$$a = \frac{Z_c - Z_1}{Z_c + Z_1} = \frac{22 - 519{,}637}{22 + 519{,}637} = -0{,}9188$$

$$b = \frac{Z_1 - Z_c}{Z_1 + Z_c} = \frac{519{,}637 - 22}{519{,}637 + 22} = 0{,}9188$$

$$a' = \frac{2Z_c}{Z_c + Z_1} = \frac{2 \times 22}{22 + 519{,}637} = 0{,}0812$$

$$b' = \frac{2Z_1}{Z_1 + Z_c} = \frac{2 \times 519{,}637}{519{,}637 + 22} = 1{,}9188$$

For the steepness of the first incident wave, the steepness time of the wave entering the substation or transformer must be determined, and the value obtained:

$t = 2\; \mu sec$

$A \;=\; 1.000\; kV$

$\alpha = A \,.\, a' = 1.000 \times 0{,}0812 = 81{,}235$

Next, determine the voltage value at the point of connection of the air wire cable voltage starting at t = 0, and the voltage value at the next time is the sum of the previous voltage value and the damping factor. The voltage value of the reflected wave is the same as the incident wave. Then the voltage at the aerial wire-cable connection point when the lightning arrester is not present for each time is 2 μsec is:

$t = 0$ μsec; $\quad e_{t=0} = 0$

$t = 2$ μsec; $\quad e_{t=2} = e_{t=0} + \frac{\alpha^1}{10^0}$

$$= 0 + \frac{81{,}235^1}{10^0} = 81{,}235\; kV$$

$t = 4$ μsec; $\quad e_{t=4} = e_{t=2} = 81{,}235\; kV$

$t = 6$ μsec; $\quad e_{t=6} = e_{t=4} + \frac{\alpha^1}{10^0} + \frac{\alpha^3}{10^4}$

$$= 81{,}235 + \frac{81{,}235^1}{10^0} + \frac{81{,}235^3}{10^4}$$

$$= 81{,}235 + 81{,}235 + 53{,}608$$

$$= 216{,}079\; kV$$

$t = 8$ μsec; $\quad e_{t=8} = e_{t=6} = 216{,}079\; kV$

$t = 10$ μsec; $\quad e_{t=10} = e_{t=8} + \frac{\alpha^3}{10^4} + \frac{\alpha^5}{10^8}$

$$= 216{,}079 + \frac{81{,}235^3}{10^4} + \frac{81{,}235^5}{10^8}$$

$$= 216{,}079 + 53{,}608 + 35{,}377$$

$$= 305{,}065\; kV$$

$t = 12$ μsec; $\quad e_{t=12} = e_{t=10} = 305{,}065\; kV$

Then the voltage time based on the lightning arrester wavefront time ($\varDelta t$) can be determined using equation (17) as follows:

$$\Delta t = (E_a - e_{t=8})/b' \left(\frac{\alpha^3/10^4}{2}\right)$$

$$= (270 - 216{,}079\,)/1{,}9188 \left(\frac{81{,}235\,/\,10^4}{2}\right)$$

$$= \frac{53{,}921}{51{,}431} = 1{,}05\; \mu sec$$

Then the spark time of the lightning arrester (t_{SO}) at the *arrester* installation location can be determined using equation (16) as follows:

$$t_{so} = 8 + \varDelta t$$

$$= 8 + 1{,}05 = 9{,}05\; \mu sec$$

Furthermore, the discharge voltage or working voltage can be determined $\left(e_{t=9{,}05}\right)$ of the lightning arrester using equations (18) and (19) as follows:

$t = 9{,}05$ μsec; $\quad e_{t=9{,}05} = e_{t=8} + \left(\frac{e_{t=10} - e_{t=8}}{2}\right) \Delta t$

$$= 216{,}079 + \left(\frac{305{,}065 - 216{,}079}{2}\right) 1{,}05$$

$$= 216{,}079 + 46{,}647$$

$$= 262{,}726\; kV$$

$t = 10$ μsec; $\quad e_{t=10} = e_{t=9{,}05} - \left(\frac{e_{t=10} - e_{t=8}}{2}\right)(2\mu t - \Delta t)$

$$= 262{,}726 - \left(\frac{305{,}065 - 216{,}079}{2}\right)(2 - 1{,}05)$$

$$= 262{,}726 - 42{,}339$$

$$= 220{,}387\; kV$$

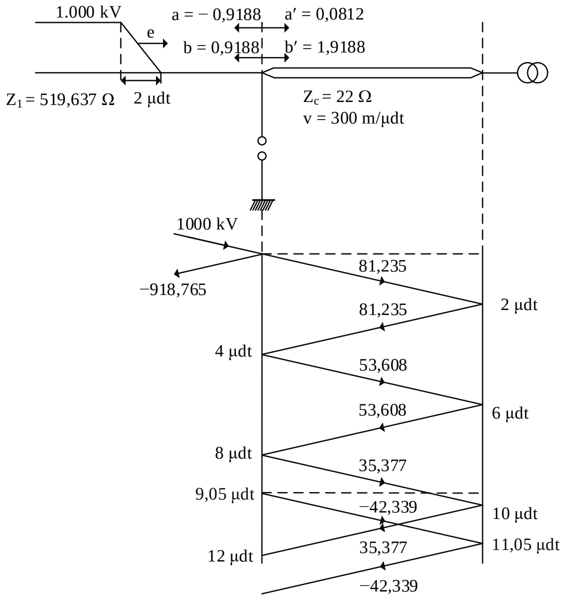


Figure 8. Lattice diagram of the lightning arrester location

6. *Determination of Maximum Distance for Arresters and Power Transformers*

At the time when $e = 262{,}726\ kV$, the lighting arrester has sparked, the sparking time of the arrester (t_{s0}) is equal to $t_{so} = 8 + \Delta t$. The voltage rise on the transformer is:

$t = 0$ µsec; $e_{t=0} = 0$

$t = 2$ µsec; $e_{t=2} = 0$

$t = 4$ µsec; $e_{t=4} = e_{t=2} + \frac{2\alpha^1}{10^0} = 0 + \frac{2\times 81{,}235^1}{10^0} = 162{,}470\ kV$

$t = 6$ µsec; $e_{t=6} = e_{t=4} = 162{,}470\ kV$

$t = 8$ µsec; $e_{t=8} = e_{t=6} + \frac{2\alpha^3}{10^4} = 162{,}470 + \frac{2\times 81{,}235^3}{10^4}$

$= 162{,}470 + 107{,}217 = 269{,}687\ kV$

$t = 10$ µsec; $e_{t=10} = e_{t=8} = 269{,}687\ kV$

$t = 11{,}05$ µsec;

$$e_{t=11,05} = e_{t=10} + \left(\frac{\frac{2\alpha^1}{10^0} + \frac{2\alpha^3}{10^4} + \frac{2\alpha^5}{10^8} - e_{t=10}}{2}\right)\Delta t$$

$$= 269{,}687 + \left(\frac{\frac{2\times 81{,}235^1}{10^0} + \frac{2\times 81{,}235^3}{10^4} + \frac{2\times 81{,}235^5}{10^8} - 269{,}687}{2}\right)1{,}05$$

$$= 269{,}687 + \left(\frac{162{,}470+107{,}217+70{,}754-269{,}687}{2}\right)1{,}05$$

$$= 269{,}687 + \left(\frac{340{,}442-269{,}687}{2}\right)1{,}05$$

$$= 269{,}687 + 37{,}090 = 306{,}777\ kV$$

$t = 12$ µsec;

$$e_{t=12} = e_{t=11,05} + \left(\frac{\frac{2\alpha^1}{10^0} + \frac{2\alpha^3}{10^4} + \frac{2\alpha^5}{10^8} - e_{t=10}}{2}\right)(2\mu t - \Delta t)$$

$$= 306{,}777 - \left(\frac{\frac{2\times 81{,}235^1}{10^0} + \frac{2\times 81{,}235^3}{10^4} + \frac{2\times 81{,}235^5}{10^8} - 269{,}687}{2}\right)(2 - 1{,}05)$$

$$= 306{,}777 - \left(\frac{162{,}470+107{,}217+70{,}754-269{,}687}{2}\right)0{,}95$$

$$= 306{,}777 - \left(\frac{340{,}442-269{,}687}{2}\right)0{,}95 = 306{,}777 - 33{,}608$$

$$= 273{,}169\ kV$$

$t = 14$ µsec; $e_{t=14} = e_{t=12} = 273{,}169\ kV$

7. *Distance of Lightning Arrester to Power Transformer*

The distance of the lightning arrester to the power transformer can be determined using equation (20) as follows:

$$S = (E_p - E_a)\frac{v}{2A}$$

$$= (306{,}777 - 262{,}726)\frac{300}{2\times 1.000} = (44{,}051)\ 0{,}15$$

$$= 6{,}6077\ m$$

8. *Insulator Breakdown Voltage in Air*

The amount of voltage arising on the transmission insulator depends on the two lightning parameters, namely the peak and steepness of the lightning wavefront. Not all lightning strikes can cause a fire jump on the insulator because it also depends on the amount of voltage that arises and does not exceed the breakdown voltage on the insulator ($E_{50\%}$). To determine the breakdown voltage of the air insulator, equation (21) is used, namely:

$$E_{50\%} = \left(K_1 + \frac{K_2}{\Delta_t^{0,75}}\right)10^3$$

$$= \left(0{,}4 \times 0{,}886 + \frac{0{,}71\times 0{,}886}{1{,}05^{0,75}}\right)10^3$$

$$= \left(0{,}3544 + \frac{0{,}6291}{1{,}0361}\right)10^3 = (0{,}3544 + 0{,}6071)10^3$$

$$= 961{,}5449\ kV$$

9. *Nominal Discharge Current*

The nominal discharge current is the current with a certain peak price and waveform that is used to determine the class of the arrester according to its current capability and protective characteristics. For the discharge current in a travelling wave event, it can be determined by using equation (22), namely:

$$I_a = \frac{2E_{50\%} - E_a}{Z_1}$$

$$= \frac{2 \times 961{,}5449 - 262{,}726}{519{,}6368} = \frac{1.660{,}3640}{519{,}6368} = 3{,}1952\ kA$$

10. *Protection Factor of Surge Arrester*

The lightning arrester protection factor of the power transformer can be determined using equation (23) as follows:

$$FP(\%) = \frac{BIL - Protection\ Level\ of\ Surge\ Arrester}{TID} \times 100\%$$

$$= \frac{325 - (262{,}726 + 262{,}726 \times 10\%)}{325} \times 100\%$$

$$= \frac{325 - 288{,}998}{325} \times 100\% = \frac{36{,}002}{325} \times 100\%$$

$$= 0{,}110774 \times 100\% = 11{,}0774\%$$

C. *Discussion*

Surge voltage or surge voltage is a sudden increase in electrical voltage that can result from disturbances such as lightning strikes or switching operations. Without a lightning arrester, surge voltages can reach very high values, potentially damaging electrical equipment. Lightning arresters serve to dampen these voltages, conduct them to ground, and protect the equipment.

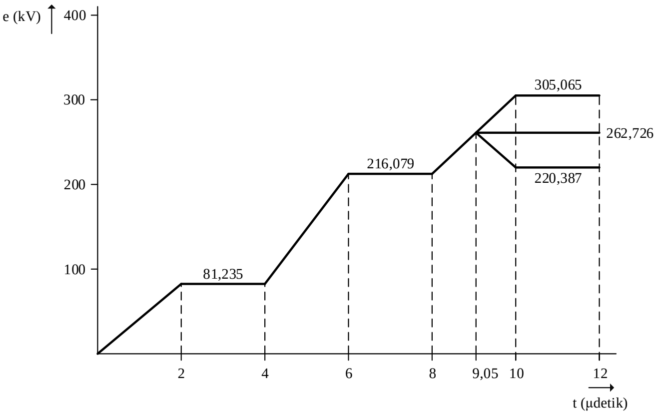


Figure 9. Voltage at lightning arrester location

Figure 9 shows that without lightning arresters, the surge voltage rises continuously until it reaches a value of 305.065 kV at t = 10 µsec. This indicates the potential risk of damage to electrical equipment exposed to such voltage surges. With the lightning arrester, the surge voltage starts to be suppressed at t = 9,05 µsec when the voltage reaches 262.726 kV. The lightning arrester serves to dampen the surge, by reducing the voltage to 220,387 kV at t = 10 µsec. This shows that lightning arresters are effective in reducing the ever-increasing surge voltage, providing protection for electrical equipment.

The clamping voltage on a transformer is the maximum voltage allowed at the terminals of equipment protected by protection devices such as lightning arresters when a voltage surge or surge occurs. This voltage is the value set by the arrester to protect the equipment by preventing the voltage from rising above a level that could cause damage.

Figure 10 shows that without lightning arresters, the clamping voltage on the transformer continues to increase uncontrollably when a voltage surge occurs. At t = 12 µsec, the pinch voltage reaches 340,442 kV. This indicates a serious risk to the transformer as the pinch voltage exceeds the BIL (Basic Insulation Level) of the transformer which is 325 kV. Voltages this high have the potential to damage the insulation and internal components of the transformer, increasing the likelihood of equipment damage and system disruption. With a lightning arrester installed, the pinch voltage at the transformer can be controlled and dampened. The pinch voltage attenuation process, at t = 11,05 µsec, the pinch voltage reached 306,777 kV and began to be attenuated by the lightning arrester. At t = 12 µsec, the pinch voltage dropped to 273,169 kV.

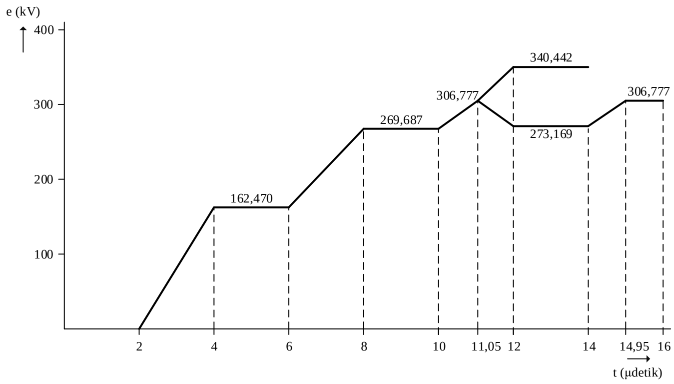


Figure 10. Increasing voltage on the transformer

The installed lightning arresters successfully limited the surge voltage to a safe value. With the lightning arresters, the clamping voltage remains below the BIL (325 kV) of the transformer, indicating that the equipment is well protected from voltage surges that could cause damage. Lightning arresters are effective in dampening voltage surges, keeping the pinch voltage at a safe level for the transformer.

Based on the calculation results, the optimal distance for the placement of lightning arresters to the 30 MVA power transformer at Bungaran Substation Palembang is 6,6077 m. While the distance of the lightning arrester installed is 7 metres, this placement is still within the limits set by PT PLN. According to SPLN 7: 1978, for 66 kV systems with double-circuit transmission, the allowed distance is up to 34 m, and for single-circuit transmission, the allowed distance is up to 17 m. Thus, the placement of lightning arresters at a distance of 7 m from power transformers remains within safe limits and complies with applicable standards, ensuring effective protection against voltage surges and surge disturbances.

The lightning arrester at Bungaran Substation Palembang has provided good enough protection to the 30 MVA Power Transformer. The protection level of 288,998 kV with a protection factor of 11,0774% ensures that surge voltages are well damped, keeping the voltage received by the transformer below the equipment's basic insulation level (325 kV). This indicates that the installed lightning arrester is able to protect the transformer from surge disturbances effectively, reducing the risk of damage due to voltage surges.

CONCLUSIONS

1. Surge voltage is a sudden increase in mains voltage due to disturbances such as lightning strikes or switching operations. Without lightning arresters, surge voltages can reach very high values of 305,065 kV at t = 10 µsec, potentially damaging electrical equipment. With lightning arresters, this voltage is dampened to 262.726 kV at t = 9,05 µsec and reduced to 220,387 kV at t = 10 µsec. This shows that lightning arresters are effective in reducing surge voltages, providing adequate protection for electrical equipment.
2. Pinch voltage is the maximum voltage allowed at the terminals of equipment when a voltage surge occurs.

Without lightning arresters, the pinch voltage at the transformer can increase to 340,442 kV at t = 12 μsec, exceeding the BIL (325 kV), which risks damaging the insulation and transformer components. With lightning arresters, the pinch voltage starts to be dampened to 306,777 kV at t = 11,05 μsec and drops to 273,169 kV at t = 12 μsec. The lightning arrester keeps the pinch voltage below the BIL, protecting the transformer from damage.

3. The optimal placement of lightning arresters against the 30 MVA power transformer at Bungaran Substation Palembang is 6,6077 m, while the installed distance is 7 m. This is still within the limits set by PT PLN, where for 66 kV systems with double-circuit transmission, the allowable distance is up to 34 m, and for single-circuit transmission up to 17 m. Thus, the placement of lightning arresters at a distance of 7 m complies with the applicable standards, ensuring effective protection against voltage surges and surge disturbances.
4. The lightning arrester at Bungaran Palembang Substation provides good protection to the 30 MVA Power Transformer, with a protection level of 288,998 kV and a protection factor of 11,0774%. This ensures the surge voltage is well dampened, keeping the voltage the transformer receives below the BIL (325 kV). The lightning arrester effectively protects the transformer from surge disturbances, reducing the risk of damage from voltage surges.

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