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Analysis of Placement and Rating Selection of Lightning Arresters for 20 kV Distribution Networks - A Case Study

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ABSTRACT

Disturbances caused by lightning strikes in the electric power system may occur in the transmission and distribution area. This paper aim is to analysis of placement and rating selection of lightning arresters for 20 kV distribution networks. A case study was conducted in the network assets of PT. PLN (Persero) at the Maroko feeder, Rayon Duri, Indonesia. This study method employed a quantitative analytical approach to evaluate the optimal placement and rating selection of 5 kA and 10 kA distribution-class lightning arresters within the 20 kV network of PT. PLN (Persero) Rayon Duri. The results of placement and arrester rating for the Maroko feeder revealed the voltage rating specification of 19.2 kV and a current of 10 kA. It was expected that the arrester can minimize lightning strike disturbances that cause induction. The results obtained after conducting simulations, the arrester can reduce a fairly large voltage quickly with a distance of 5.6334 meters from the disturbance and the duration of 1.2 - 50 µs. Therefore, placing the arrester in close proximity to the equipment significantly improves insulation coordination by accelerating the suppression and safe discharge of lightning-induced surges.

KEYWORDS: *Lightning Arrester Rating, Maroko Feeder, ATP Draw.*

1. INTRODUCTION

The reliability of distribution networks is strongly influenced by their ability to withstand lightning-induced over voltages, particularly in tropical countries such as Indonesia. Lightning surges can propagate through overhead distribution lines, resulting in insulation breakdown, transformer failures, feeder outages, and significant economic losses [1-4]. Lightning arresters therefore play a critical role in limiting transient over voltages by diverting surge currents to ground before they reach sensitive equipment. However, the protective performance of a lightning arrester is governed not only by its electrical characteristics but also by the appropriateness of its installation location and discharge current rating. Inadequate placement or improper arrester selection may reduce the protection margin and increase the probability of insulation failure despite the presence of surge protection devices.

In 20 kV distribution networks, selecting the appropriate arrester rating, such as 5 kA or 10 kA, requires consideration of the expected lightning current, insulation coordination, grounding characteristics, feeder configuration, and the location of critical assets such as distribution transformers [5-8]. Furthermore, studies have demonstrated that the relative position of lightning arresters with respect to fuse cut-outs and transformers substantially affects surge attenuation and transformer protection effectiveness [1],[9-10]. Consequently, a comprehensive assessment of arrester placement and rating is essential to achieve optimal technical performance while maintaining cost-effective protection of distribution equipment [11-15].

Although numerous studies have investigated lightning protection for transmission systems, research focusing on the practical evaluation of arrester placement and rating selection in 20 kV distribution networks operated by Indonesian utilities remains relatively limited. This study addresses this gap by analyzing the placement and rating selection of 5 kA and 10 kA lightning arresters in the 20 kV distribution network of PT PLN (Persero) Rayon Duri. The analysis considers insulation coordination, arrester residual voltage, protective distance, and the suitability of each arrester rating under actual distribution network conditions. The findings are expected to provide practical recommendations for optimizing lightning protection strategies, improving distribution system reliability, reducing equipment failures, and supporting more effective asset management in medium-voltage distribution networks exposed to frequent lightning disturbances.

In the PT. PLN Persero Rayon Duri system, there are several areas that often experience quite large lightning strikes, one of which is in the distribution network on the Maroko feeder. The Maroko feeder connects from the Balai Pungut Duri 150/30 MVA – 20 kV GI with an output to the Belutu GH, which it divided into 3 paths. The Maroko distribution network spans 203.48 km. Based on the results of data analysis from PT. PLN Persero Rayon Duri in 2023, the number of lightning strikes resulted in lightning strikes to the distribution transmission network approximately 35 times, in 20 kV distribution network feeders. Based data, there were 28 lightning strikes to the Maroko feeder and approximately 8 times, which caused blackouts to the Maroko feeder during 2023.

Several factors that are needed and must be considered when choosing lightning arrester for 20 kV distribution networks according to SPLN D5.006: 2013 [16], also commonly using the maintenance and condition assessment manual for power system equipment, to suit its use as follows:

1. Continuous operating voltage and rated voltage arrester equation [16].

$$\text{Ur,min} = 0.8 \text{ x Um,min} \tag{1}$$

Information:
Ur,min = Minimum rated voltage
Um,min = Highest system voltage for equipment
0.8 = Coefficient value for direct grounding

The rated voltage value (Ur) is obtained by multiplying the actual continuous operating voltage value by a grounding error factor of 1.25.

2. Residual voltage / working voltage arrester:

$$\text{IM} = (\frac{BIL}{TO} - 1) \text{ x } 100\ \% \tag{2}$$

Information:
IM = Impulse Margin (%)
TO = Maximum discharge voltage of the arrester (kV)
BIL = Basic insulation level (kV)

Determining Surge Wire Impedance

The surge impedance is the impedance value obtained when a surge occurs, whether it is a lightning surge or a circuit surge. Surge impedance is also influenced by the constant *L* and *C* which propagates in the conducting wire, where both constants are also influenced by the characteristics of the wire [17]. The impedance value is the value obtained when a lightning surge or a circuit surge occurs. To determine the impedance value of the surge wire is shown in Equation (3).

$$Z=\sqrt{L/C} = 60\ In\frac{2h}{r}(\Omega) \tag{3}$$

Information:
r = Wire fingers
h = Average load
Z = Surge impedance
L = Inductance
C = Capacitance

Nominal Discharge Current

The discharge current with a specific peak value and waveform is used to determine the class of arrester, which corresponds to its ability to pass current. The peak value of the surge voltage that arrives or enters the substation comes from a channel that is limited by the BIL. By considering the variations flashover and the probability of penetration of the isolator, then 20% for the safety factor, so the value of E can use Equation (4) [18].

$$Ia = \frac{2E-V}{Z} \tag{4}$$

Information:
Ia = Arrester discharge current (kA)
E = Magnitude of incoming surge voltage (kV)
Va = Terminal Voltage Arrester (kV)
Z = Surge Impedance

Determining the Number of Lightning Strikes

The higher the lightning strike density in an area, the greater the risk of protection failure from transmission lines or substations. Many researchers have paid attention to this by providing their own formulas as shown in Equations (5) and (6) 18].

$$N = 0.15\ IKL \tag{5}$$

$$N_L = 0.015\ IKL\ (b+4h^{1.09}) \tag{6}$$

Information:
N = Number of Strikes km^2/Year
IKL = Number of Thunder Days/Year
b = The physical width of the structure (meters)
h = The total height of the structure (meters)

Maximum Distance Placement of Lightning Arrester with Equipment

The protection distance calculation maximum lightning arrester with the equipment to be protected, this is done to find out at what distance lightning arrester capable of protecting the equipment it protects. The calculation of the wave front of the transmission cable can be used the Equation (7) or (8) [18].

$$\frac{dv}{dt} = \frac{1}{2} x\ Zs\ x \frac{di}{dt} \tag{7}$$

Information:
$\frac{dv}{dt}$= Lightning Current Steepness Value (kA/us)
Z_S = Surge Impedance (ohms)

$$l = \frac{Ut-Ua}{2x\frac{df}{dt}} \times v \tag{8}$$

Information:
L = Distance between lightning arrester (m)
Ut = Basic isolation level (BIL) of protected equipment (kV)
Ua = Residual voltage of the lightning arrester (kV)
$\frac{df}{dt}$ = Steepness of the incoming wave (kV/µs) value ranges between 1000 kV/µs - 2000 kV/µs
V = Wave propagation speed (300 m/µs for overhead lines, 150 m/µs for cables

Influence of Soil Structural Conditions

Measurement of soil resistivity with non-homogeneous soil composition has variations both vertically and horizontally, so that in certain layers there are two or more

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types of soil with different resistivity causing it to be impossible to determine a fixed value. It is better to obtain a fixed value by conducting direct measurements on site by increasing the number of measurement points. Regarding soil resistivity is presented in Table 1.

Table 1: Effect of temperature on soil resistivity

No	Temperatur (°C)	Resistivitas (Ω)
1	-5	70.000
2	0	30.000
3	10	8000
4	20	7000
5	30	6000
6	40	5.000
7	50	4.000

A rod type of electrode is used for grounding in a 20 kV medium voltage distribution network. The rod electrode is an electrode made of steel pipe or metal rod, which is inserted deeply into the ground until it reaches a good grounding value. To determine the size of the grounding resistance with one rod electrode, Equation (9) is used [19].

$$Rbt = \frac{P}{2\pi L}\left(In\ \frac{4L}{d} - 1\right) \quad (9)$$

Information:
Rbt = Grounding resistance of rod electrode (Ω-m)
P = Soil resistivity (Ω-m)
L = Length of embedded stem (m)
d = Diameter of the electrode rod (m)

To calculate the grounding value can be reduced using a parallel system grounding by increasing the number of electrode installations, namely by connecting existing electrodes in parallel with new electrodes. This can be seen using Equation (10) [19].

$$\frac{1}{Rtot1} = \frac{1}{R1} + \frac{1}{R2} + \ldots.. + \frac{1}{Rn} \quad (10)$$

Information:
Rtot = Total Resistance Value (Ω)

Electromagnetic Transients Program (EMTP)

The EMTP program can estimate the output of a specific variable (voltage or current) in an electrical circuit as a function of time, which is usually subject to disturbances. The Alternative Transients Program (ATP) provides numerous models of electrical components, such as motors, generators, transformers, lightning arresters, transmission lines, and cables. ATP also provides a program module for analyzing transient conditions in control systems. This facility is commonly known as TACS (Transient Analysis of Control System).

Using the TACS facility, it is possible to analyze the transient response of the control system to symptoms or nonlinear disturbances such as surges and corona symptoms. TACS is also able to analyze the dynamic characteristics of the system without going through the depiction or modeling of the system as an electrical circuit. The ATP can be used for simulations in symmetrical or asymmetrical conditions of disturbances, lightning surges. The ATP is also able to analyze the harmonic effects of a system with the harmonic current injection method [20].

2. METHOD

This study employed a quantitative analytical approach to determine the optimal placement and rating selection of lightning arresters in the 20 kV distribution network of PT. PLN (Persero) Rayon Duri using technical specification data for 10 kA and 5 kA distribution-class lightning arresters. The analysis was based on the feeder single-line diagram, network configuration, transformer capacity, conductor characteristics, grounding resistance, and the electrical characteristics of the arresters. The specification data for the lightning arrester 10 kA and 5 kA used in the 20 kV distribution network of PT. PLN (Persero) Rayon Duri as showed in Table 2. The single line electricity load on the Maroko feeder belonging to PT. PLN (Persero) Rayon Duri is shown in Figure 1.

Table 2: The lightning arrester specifications

No	Specification	Unit	Neutral point grounding system (solid/effective)
1	Fault current duration	second	≤ 1
2	Rated voltage (Ur)	kV	≥ 21
3	Operating voltage continuous (Uc)	kV	≥ 16.8
4	Isolator type	-	Polymer
5	Terminal material phase/ground	-	Stainless Steel
6	Rated Frequency (Fr)	Hz	50
7	Highest voltage for equipment (Um)	kV	24
8	Nominal discharge current identifier (8/20 μs) (In)	kA	10
9	Connectivity ability short sheath for 0.2 seconds	kA rms	≥ 20
10	Residual stress Maximum	kVp	< 58
11	Withstand voltage impulse (wave 1.2/50 μs)	kVp	≥ 125
12	Disconnected	-	Yes

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The analysis methodology for the placement and selection of 20 kV lightning arrester ratings begins with the collection of technical data in the form of the transformer's Basic Insulation Level and the specifications of the 5 kA and 10 kA discharge voltage and current. The next stage involves evaluating the suitability of the arrester voltage rating to the system voltage, followed by technical calculations using the insulation coordination formula to determine the maximum permissible installation distance so that the surge voltage does not exceed the transformer's insulation threshold. This analysis is then validated by calculating the protection margin to ensure the safety level, as well as comparing the current withstand performance between the 5 kA and 10 kA ratings based on the effectiveness of the protection and field disturbance data to produce the most optimal technical recommendations for the distribution network.

Working voltage characteristics lightning arrester at PLN according to SPLN T5.006-2013 [16], for determining the level of isolation transformer and lightning Arrester can be seen in Table 3. Based information on Table 3, it can do an analysis of which selection would be made for rating lightning arrester to be installed. The selection rating lightning arrester suitable for use in high voltage networks or in medium voltage networks in the future.

Table 3: Working voltage characteristic data of lightning arrester

Specification	Nominal voltage		
	150	66	20
	kV		
High voltage for equipment.	170	72	24
Grounding.	Effective	Home	Home
Transformer (rated voltage/side high voltage.	150	66	20
Basic isolation level.	650	325	125
Lightning Arrester Rated voltage.	138	75	24
Nominal discharge current.	10 kA	10 kA	5 kA
Discharge voltage.	460	270	87
Wave front pulse splash voltage.	530	310	100
Standard pulse spark voltage.	460	270	87
Class.	10 kA	10 kA	10 kA

(Source: SPLN T5.006-2013 [16])

For existing data on the Maroko feeder, such as feeder length data is shown in Table 4. The lightning strike point disturbance data depicted in Table 5 and for recloser zone data on the Maroko feeder in Table 6. Grounding measurement lightning arrester data related to the results of measuring the grounding value samples on the Maroko feeder at each location can be seen in Table 7.

Table 4: Feeder Length (Maroko)

No	Name of Refiller	Length (Kms)
1	Argentina	32.35
2	Brazil	29.2
3	Venezuela	40.9
4	Because	47.25
5	Chile	33.55
6	Panama	141.35
7	Cameroon	111.93
8	Kongo	193.9
9	Egypt	166.5
10	Maroko	203.48
11	Bolivia	28.8
	Total Length	1000.41

(Source: PT. PLN (Persero) Duri Rayon, 2023)

Table 5: Technical data of lightning strikes on Maroko feeders

No	Disturbance Point	Unit	Amount
1	PMT Jurs Tapung	Time	1
3	RC-01 Highlands	Time	4
2	RC-02 Lancang Lake	Time	1
3	PMT Jurs Sukatani	Time	2

Source: PT. PLN (Persero) Duri Rayon 2023)

Table 6: Zone of recloser on the Maroko feeder

Zone	Distance from Substation	Condition	Brand
1	26,15 km	Normally Close	Schneider Electric
2	17.40 km	Normally Close	Schneider Electric
3	39,55 km	Normally Close	Schneider Electric

(Source: PT. PLN (Persero) Rayon Duri, 2023)

Table 7: The grounding measurement results

Location	Soil Type	Results (Ohm)	Information
RC-01 Highlands	Land of Padas	12.8	Recloser + Arrester
RC-02 Lancang Lake	Clay Sand	3.7	Recloser + Arrester
RC-03 Dusun Tiga	Clay Sand	8.23	Recloser + Arrester
PMT GH Jurs Tapung	Clay Sand	2.73	PMT + Arrester
PMT GH Jurs Sukatani	Clay Sand	3.8	PMT + Arrester
PMT GH Jurs Pasar Minggu	Clay Sand	3.6	PMT + Arrester

(Source: PT. PLN (Persero) Duri Rayon 2024)

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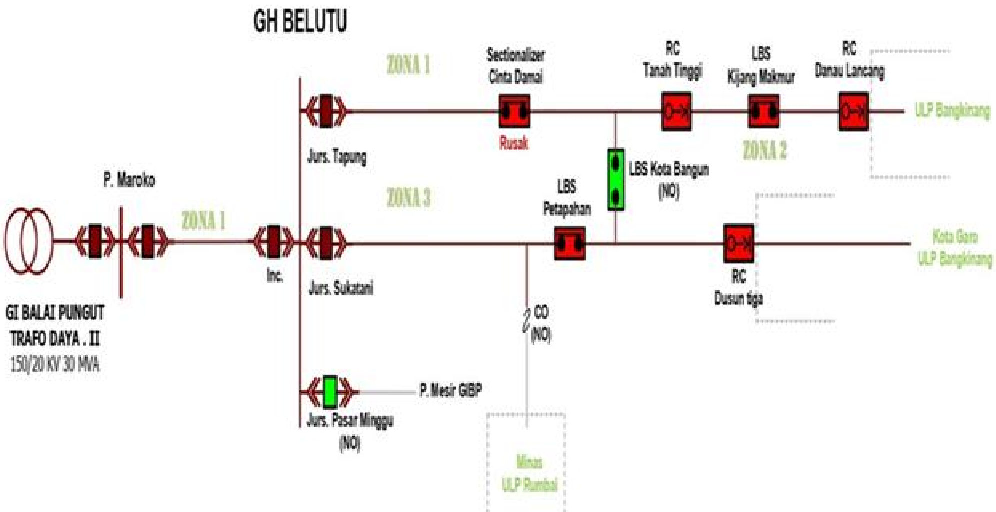

Figure 1: Single line feeder in Maroko

3. RESULT AND DISCUSSION

3.1 Analysis of Rating Lightning Arrester

The rating lightning arrester analysis was carried out regarding the value rating from lightning arrester. Election on rating lightning arrester was refer to the continuous operating voltage and rated voltage arrester 21 kV; a = 0.8; Um, min = 24 kV; Hour, min = 0.8 x Um, min; Clock, min = 0.8 x 24 kV and Clock, min = 19.2 kV.

The minimum rated voltage result was 19.2 kV. This rated voltage value was used to deal with isolated over voltages that have a relatively long duration or Temporary Over Voltage (TOV). The rated voltage value can be obtained from the result of multiplying the continuous operating voltage value (Uc) by the grounding error factor of 1.25. Basically, the relationship between Ur and Uc: Ur = Ur,min rounded to the next value divisible by 3 = 21 kV. The grounding error factor was 1.25; Uc = Ur/1.25 ; Uc = 16.8 kV and residual arrester voltage was 21 kV.

The voltage was generated at the terminal arrester releasing the discharge current flowing to ground. So, using the IEC standard, the current impulse was 8/20 μs with a peak discharge current value of 10 kA. On the datasheet lightning arrester 21 kV used a working voltage value of 58 kV. So, the working voltage must not exceed the BIL of the protected equipment even though the maximum discharge current reaches 65 kA up to 100 kA.

3.2 Determining Wire Impedance

The grounding wire was used type of AAAC (A3C) or LVTC with a cross-sectional area of 35 mm in diameter. This grounding wire has a length of 11 meters from the ground surface and a diameter of 11 mm, so its radius (r) was 6 mm = 0.0055 m. The impedance value of the surge wire can be calculated as follows: h = 11 m; r = 0.0055 m; Zs = 60 In $\frac{2h}{r}$; Zs = 60 In $\frac{2 \times 11}{0{,}0055}$; Zs = 497.64 Ohm. The resulting surge impedance value was 497.64 Ω. In this case, the surge impedance value is influenced by the length of the grounding conductor and the diameter of the conductor used in the grounding.

3.3 Determination of Nominal Discharge Current

The insulators used in the Maroko feeders Zone 1 using pin insulators that have an impulse surge voltage of 125 kV per piece. The insulator pins on the distribution network were 20 kV. Each 20 kV high voltage overhead power line (SUTM) pole has 3 insulator pins, so the surge voltage, surge, impulse or BIL on the line was 3 x 125 kV. Hence, the value of the incoming surge voltage with time line of 3 x 125 kV = 375 kV; E = 1.2 x BIL of line; E = 450 kV.

The nominal discharge current lightning arrester used to determine the class of lightning arrester with a maximum residual voltage of 58 kV. E = 450 kV; Ea = 58 kV; Z = 497.64 Ohm; Ia = 1.69 kA. So, the nominal discharge current was 1.69 kA and this value was appropriate for using a nominal peak discharge current of 10 kA.

3.4 Determination of Protective Factors Arrester

The protective factors arrester was the magnitude of the voltage difference between the TID of the protected equipment and the working voltage arrester. A good protection factor (FP) should not be < 20% with Ea of 58 kV and PL of 63.8 kV. The protection level (PL) has a value of 63.8 kV, which was used to find the FP value and the transformer BIL value of 125 kV by looking at datasheet. Therefore, the BIL transformer of 125 kV; PL = 63.8 kV and FP was 48.96 %. The protection factor value obtained was 48.96%. This result is good because it can exceed 20% (>20%).

3.5 Simulation Results Using ATPDraw-EMTP

The result of the ATP-Draw simulation for the difference in lightning surge disturbance waves on a 20 kV distribution network, with the circuit shown in Figure 2. The comparison results used rating lightning arrester between 5 kA and 10 kA. So, it can later be seen for arrester works to reduce peak voltage disturbances from lightning surges. For peak voltage disturbance waves using a rating of 5 kA can be seen in Figure 3 and a rating of 10 kA can be seen in Figure 4. It can be seen from Figure 3 and 4 for a comparison of capabilities of the rating arrester of 5 kA with 10 kA in absorbing the disturbance that occurs.

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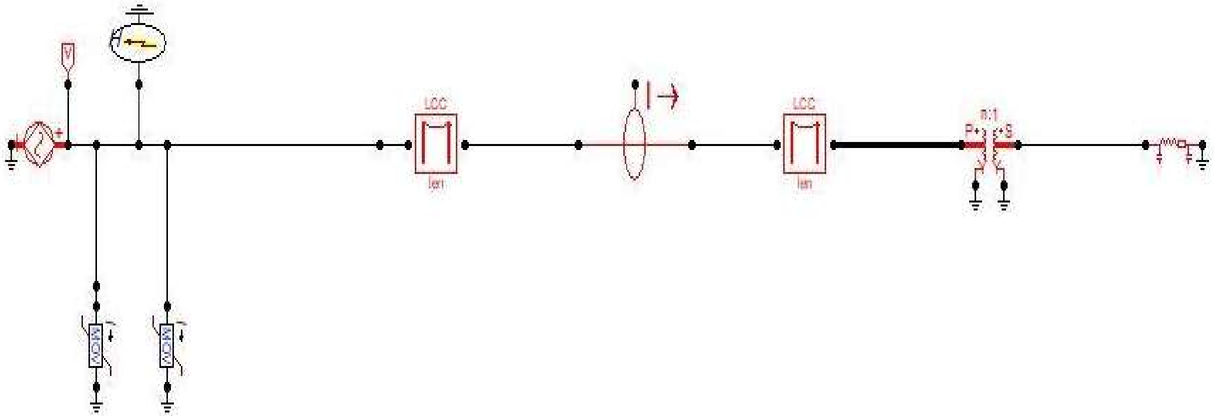

Figure 2: The ATPDraw – EMTP simulation circuit

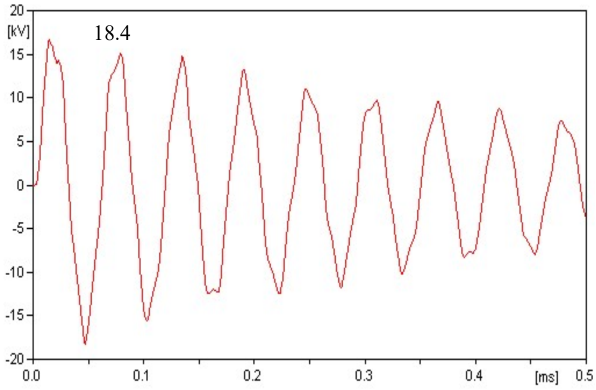

Figure 3: Peak voltage waveform of 5 kA arrester rating with front time (1.2/50 is)

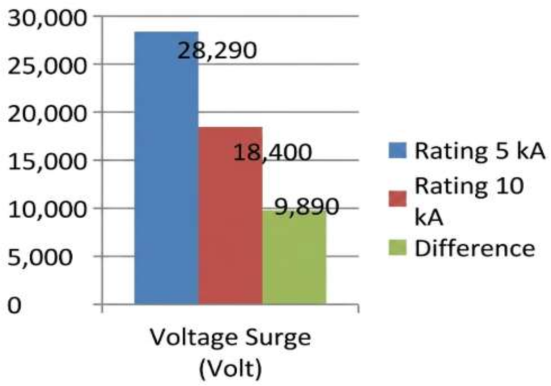

Figure 5: Comparison chart of the use of arrester ratings of 5 kA and 10 kA

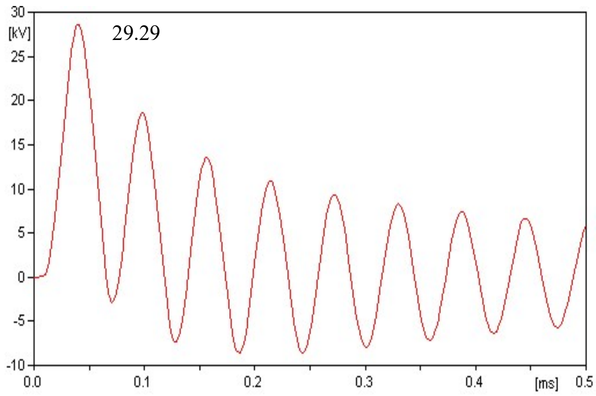

Figure 4: Peak voltage waveform of 10 kA arrester rating with front time (1.2/50 µs)

The result of rating arrester of 5 kA peak working voltage arrester was 28,290 Volts. The rating arrester for 10 kA resulted of 18,400 Volts. For comparison, reducing the peak working voltage of the arrester between 5 kA and 10 kA was revealed a result of 9,890 Volts. The comparison graph can be seen in Figure 5.

The value of placement distance analysis lightning arrester was determined from the surge impedance value (Zs) and the steepness of the cable conductor surface (*dv/dt*). Then, it can be calculated by using Equation (7). Based the calculation for distance between lightning arrester resulted 2,817.09 kV/ µs for the steepness of the incoming lightning wave on the distribution network at GH.

Hence, the calculation of maximum protection distance lightning arrester was carried out with the aim of finding out at what distance lightning arrester able to protect the equipment that will be protected later in this case PMT switching substation. Value of *l* from the result of the calculation analysis using the Equation (8) was resulted 5.6334 meters, which was the maximum protection distance of lightning arrester for *Belutu* distribution substation equipment.

A grounding electrode is a device implanted and used to conduct lightning current into the ground through a grounding wire. The electrode used at PT PLN Persero Rayon Duri used a rod electrode. This rod electrode was made of a metal rod pipe (galvanized) that was 2 meters long and 2 inches in diameter or 5.080 cm. To determine the effect of the size of the grounding resistance with a single rod electrode was calculated using Equation (9). Where the conditions in the clay or yellow soil location, ρ = 100 Ohm; R= 31.2548 Ohm. The grounding resistance value of the rod electrode was 31.2548 Ohm with yellow soil conditions (field soil). At this value (R > 5 Ohm), hence it did not meet the requirements specified by the maximum value of 5 Ohm. Therefore, it was conducted the grounding repair with the addition of rod electrodes.

In the yellow soil condition, a parallel grounding system can be used, with a grounding value of 31.2548 Ohm. So, to calculated the number of electrode rods were in parallel to produce resistance up to (R < 5 Ohm) was used Equation (10). The total grounding resistance was determined through a sequential iterative process based on the parallel circuit principle for eight individual electrodes, each possessing a baseline resistance of 31.2548 Ω. By applying the Equation (10), the equivalent resistance was calculated step-by-step, commencing with an initial pair that yielded Rtot1 of 15.62 Ω and progressively integrating the remaining components. This analysis demonstrates a continuous reduction in the overall resistance, descending through Rtot2 of 10.41 Ω, Rtot3 of 7.80 Ω, Rtot 4 of 6.24 Ω, Rtot5 of 5.20 Ω, and Rtot6 of 4.45 Ω, before culminating in a final value of Rtot7 of 3.89 Ω.

From the calculation results obtained, a graph can be made to view and analyze the iron rod electrode (galvanized) each additional rod electrode is calculated in parallel grounding, can be seen in Figure 6. These outcomes confirm that increasing the number of parallel pathways effectively minimizes the total grounding resistance, which is a critical parameter for optimizing the protection capabilities of the 20 kV distribution network against lightning surges.

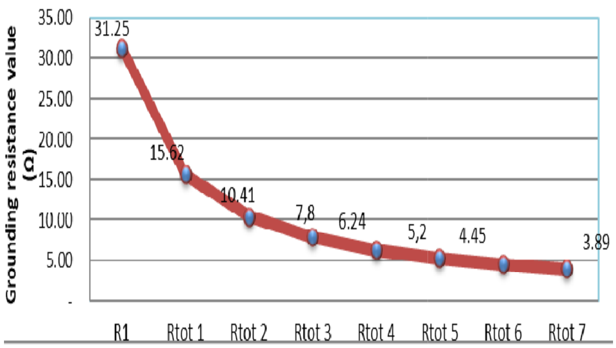

Figure 6: Graph results of the parallel electrode rod value

4. CONCLUSION

Based on the quantitative analysis conducted on the 20 kV Maroko feeder at PT. PLN (Persero) Rayon Duri, this study achieved the optimization of lightning protection relies on a precise combination of hardware rating, spatial coordination, and grounding integrity. The investigation confirms that selecting a 10 kA lightning arrester with a 21 kV rated voltage is the superior technical choice compared to a 5 kA unit, as the 10 kA rating achieved a significant voltage suppression of 18,400 Volts and the outperforming of the 5 kA 9,890 Volts. Furthermore, based on the ATPDraw–EMTP simulations validated that reducing the installation distance from 13 meters to a safe separation of 5.6334 meters is critical for rapid surge discharge and effective insulation coordination. Finally, to mitigate risks associated with high soil resistance, the study successfully reduced grounding levels below the 5 Ohm threshold by implementing a multi-rod galvanized electrode system at key locations, including RC-*Tanah Tinggi* and RC-*Dusun Tiga*. Collectively, these adjustments provide a robust defense mechanism, significantly minimizing lightning-induced induction and enhancing the overall reliability of the distribution network. Future work can be conducted for comparative analysis across different utilities (PLN regions) to develop standardized guidelines for lightning protection in tropical distribution networks, considering regional variations in lightning density and soil conditions.

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