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Reduced Dielectric Losses for Underground Cable Distribution Systems

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ABSTRACT

This paper describes the process to reduce dielectric losses for underground cable distribution system. As already known, that system is an alternative solution to energy distribution systems in urban areas. Influence of large capacitance is a separate issue that needs to be resolved. Large capacitance effect on Express Feeder of 10 miles long has resulted in power losses more than 100 MW per month. In the no-load condition, current dispatch has recorded 10 Amperes, and has increased the voltage at receiving end by 200-500 Volts, with leading power factors. Installation of the inductor to reduce cable loss dielectrics is done by changing the power factor (pf) to 0.85 lagging. After installation of the inductor, which is 5 mH/700 kVAR, dielectric losses is reduced to 3.57%, which is from105,983 kW to 102,195 kWh per month. The capacitive leakage current has also been reduced from 249.61 Ampere to 245.17 Ampere.

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1. INTRODUCTION

The most important things required in the power system is a matter of quantity and quality of the received energy on the consumer side. Delivery quantity is required to distribute electric power to all consumers in a region or area served, so the benefits from the existence of electric energy can be felt by the public. Increasing the quantity of electric power distribution will increase the electrification ratio in an area. At the same time, the quality of distribution of electrical energy is required to maintain the availability of electrical energy consumers in accordance with the standards used.

Quantity and quality of electric energy distribution in urban areas often face problems, such as difficulty in getting right of way (ROW) for transmission and distribution networks. The land acquisition process for this purpose is not an easy thing to do at this time. This is due to the limited land that can be used for over head line.

Underground cable distribution system is an alternative solution to distribute electrical energy in urban areas, so the city will be looked magnificent and clean. However, the construction cost of underground cable per km was much higher than over head line [1]. Development of distribution network is relatively tougher because the branching process (tapping) is much harder when compared to the airways. Anyhow underground cable is more protected from wind, lightning strikes, and disturbances of animals (like monkeys), which may cause short circuit.

Musabaqoh Tilawatil Qur'an (MTQ) national level event was held in the mid-1980s at Pekanbaru, which is the capital of Riau province. In meeting the demand of electric power to serve all activities, the feeder in the district of "Simpang Tiga" and surrounding areas can no longer serve it. Thus, it needs the additional feeder in order to serve the requirements of specific loads around the location of the event.

At the same time, the problem of urban congestion and the limited land that can be used as well as encouragement to pay attention to issues of beauty and scenery of Pekanbaru city should be tackled. This consequence is not possible for the addition of new feeders by using a medium-voltage over head line (OHL). Hence the utility (PLN Pekanbaru)has constructed Express Feeder using underground cable distribution between substation (SS) TelukLembu (TLB) and substation MTQ, to continue to serve the power demand.

1.1. Literature Review

The difference of voltage level between the sending and the receiving end is due to the parameters of the line system (R, L, C). If the voltage level at the receiving end is lower than on the sending end then it is caused by the influence of R and L, so it is an inductive load. Meanwhile, if the voltage level at the receiving end is larger than the sending end, this is caused by the influence of R and C, so it is a capacitive load. Both cases can be described from the phasor diagram as shown in Figure 1, where V_R= Voltage at receiving end, V_S=Voltage at sending end, R=Line Resistance, X=Line Reactance, Z=Line Impedance, I= Line current, α= phase angle between voltage and currentat receiving end, δ= phase angle between V_R and V_S.

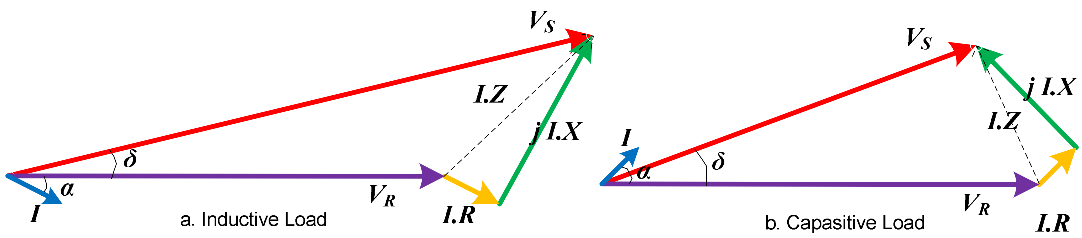


Figure 1. Power system phasor diagrams

Rules or standards used by the PLN (Persero) for the received voltage tolerance on the customer side is +5% and -10% of the working voltage (system) [2]. A large voltage drop will result in the loss of electric service to consumers and producers. The potential differences between the sending and the receiving end cannot be avoided. To keep the voltage difference is not too high on both sides, inductive reactive power or capacitive reactive power compensation is commonly used.

A lot of research has been done in an attempt to improve the voltage level at transmission or distribution line. When the voltage level at the receiving end is less than the sending end, a capacitive reactive power compensation is to be performed. If the voltage at the receiving end is greater than the sending end, then inductive reactive power compensation has to be performed. Improvement of the voltage levels will reduce the power loss in the line. The level of improvement is determined by the value of reactive power, which can be obtained by installing inductors or capacitors. Most research conducted is to increase the voltage at the receiving end due to an inductive load. However, few researches has been undertaken to reduce the voltage. Indrayanti (2011) installs an inductor at the sending end based on the load flow data obtaindon average at 17.00. Then the results were used to calculate the magnitude of dielectric losses of underground cables. [3].

On the other hand, there is also the voltage difference between the conductors and cable sheath. The voltage difference will affect the capacitancevalue of the cable.The flux distribution in alternating current (a.c) cable insulation is complex and shown in Figure 2. The stress is a maximum at the conductor surface and varies throughout the insulation. It was decreasing with distance from the conductor surface, because of the differing permittivities of the components and the distribution of the flux at various times. The screened cable used for alternating voltages has a clearly defined stress pattern, while that of cables used on direct current (d.c) transmission has a changing pattern depending on temperature due to cable loading [4].

1.2. Underground Cable Capacitance

A single core cable is infact an electrostatic capacitor because it has two electrodes, the core of the cable and the sheath separated by dielectric material. Figure 3 shows, the capacitance of the underground cable a single-core. By definition, capacitance is the ratio of the charge on one of electrodes to potential difference between the electrodes [5, 6]. Capacitance of the single core underground cable can be calculated using the equation (1) [6].

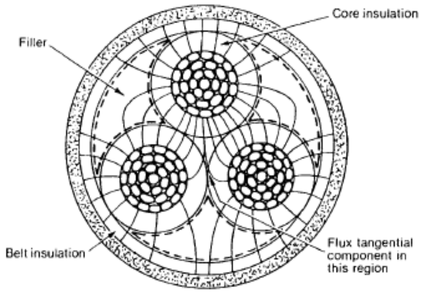


Figure 2. Flux distribution that occurs in a three-core cable.

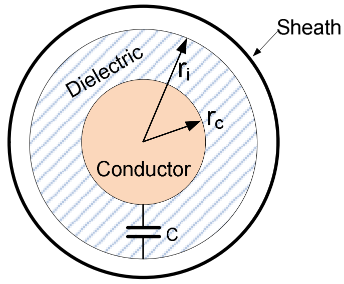


Figure 3. Capacitance of a single core cable.

$$C = \frac{2 \cdot \pi \cdot \varepsilon \cdot l}{\ln\left(\frac{r_i}{r_c}\right)} \; [\text{Farad}] \qquad (1)$$

Where; C = capacitance value for single core underground cable,r_i= the inner radius of the sheath, r_c= radius of the conductor, *l*=cable lenght, ε=permittivity of the dielectric material.

While for the three-core cable, the capacitance value can be calculated, if the dielectric is assumed uniform between the core and the sheath. However, normally it is not so and, therefore, it is desirable to find the capacitance by measurements. In a three core cable, sheath is at earth potential and the three conductors are at supply potentials. There are six capacitances form between these systems. Three capacitances are between the sheath and the conductors and the other three capacitances are between the conductors. The capacitance of three cores underground cable could be calculated using the equation (2) [6].

$$C_2 = \frac{2 \cdot \pi \cdot \varepsilon \cdot l}{\ln\left(\frac{D}{r_c}\right)} \; [\text{Farad}] \qquad (2)$$

Where D = conductor spacing.

If the distance between the conductorsareassumed symmetrical, and voltage stressesare uniformly distributed on the cable insulation. Then, as shown in Figure 4, the capacitance value can be calculated using equation (3).

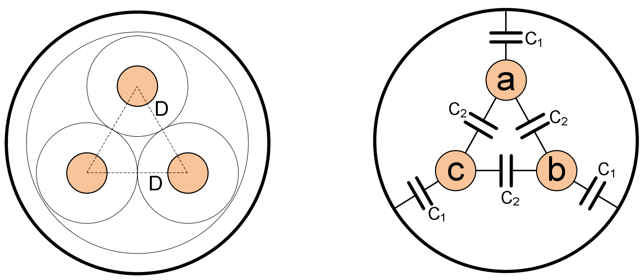


Figure 3. Capacitancesbetween cores and to sheath of a three core cable.

$$C_0 = C_1 + 3 \cdot C_2 \; [\text{Farad}] \qquad (3)$$

Where C_0 = capacitance value for three cores underground cable, C_1 = the capacitance between conductor and the sheath, and C_2 = the capacitance between each conductor.

Table 1 shows the data from the electrical underground cable of XLPE insulation materials. Compounds that have good electrical properties are required for distribution cables with operating voltages above 3 kV. IEC502 standard requires that products must have a dielectric loss angle (DLA) and the permittivity is not greater than 0.75 with a range of angles 85 °C ambient. Besides, DLA at 80 °C must not exceed the value at 60 °C. This requires that when there is an open-circuit fault occur, while the cable is being energized with a high voltage, the wires will be hot even though there is no current flowing inside it [6, 7]. Figure 5 shows the physical shape of the underground cable NA2XSEFGbY used in this analysis. The technical data is as shown in Table 2 [8].

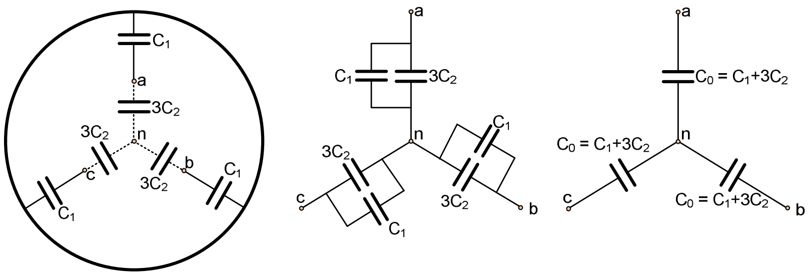


Figure 4. Equivalent capacitance of a three core cable.

Table 1. Electrical Data Crosslinked Polyethylene (XLPE) cable

Description	Value
Type	GP 8
Volume resistivity (min) at 20°C (Ω m)	1×10^{14}
Permittivity at 50 Hz	2.3-5.2
tan σ at 50 Hz	0.0004-0.005

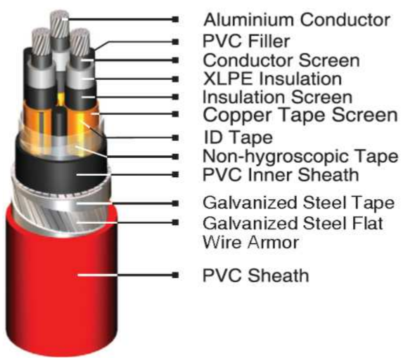


Figure 5. Underground Cable NA2XSEFGbY (Courtesy of Kabel Metal Indonesia)

The value of Inductor needs to compensate the reactive power can be determined by knowing the power factor at the sending and the receiving end. By using these two values, the addition value of inductive reactive impedance that required can be obtained in Henry and VAr.

Table 2. Electrical and Mechanical Data of NA2XSEFGbY 240 mm^2.

Description	Value	Description	Value
Cross Section of Conductor (mm^2)	240	DC Resistance at 20 ^oC (Ω/km)	0.125
Conductor Diameter (mm)	18.7	AC Resistance at 90 ^oC (Ω/km)	0.162
Insulation Thickness (mm)	55	DC Insulation Resistance at 20^oC (MΩ.km)	700
Insulation Diameter (mm)	31.3	Current Carrying Capacity in Air (A)	453
Armor Thickness (mm)	0.80	Current Carrying Capacity in ground (A)	385
Sheath Thickness (mm)	3.6	Capacitance per phase (μF/km)	0.307
Cable Weight (kg/km)	9.600	Inductance per phase (mH/km)	0.302
Min. Bending Radius (mm)	78.0	Max short circuit current of screen (kA/sec)	4.53
Overall Cable Diameter (mm)	85	Max short circuit current of conduct (kA/sec)	22.98

1.3. Underground cable Energy Losses

An underground cable consists of three main components, namely the conductor, dielectric materials, and sheath. When the cable is energized by a voltage electric, current will flow, and will heat the cable. The temperature rise of a cable body depends upon the rate of generation and dissipation of heat by the body. Thermal effects that occurred will result in losses. The losses are; (1) conductor losses, (2) dielectric losses, and (3) sheath losses [6].

This paper discusses the dielectric losses in underground cables, which is one of the three types of electric losses associated with an underground cable. As already known, that if it is energized with alternating current there will be a large capacitance effect, so it will involve the phase voltages and power factors. For single core cables, the dielectric loss can be calculated using the equation (4) [4, 6].

$$P_{D_1} = 2 \cdot \pi \cdot f \cdot C \cdot \tan\sigma \cdot V^2 \ \left[\text{Watt}\right] \quad (4)$$

where :

P_{D_1}	=	Dielectric Loss [Watt]
f	=	Frequency [Hz]
C	=	Capasitance [Farad/meter]
V	=	Line to netral Voltage [Volt]
tan σ	=	Dielectric Loss Angle (DLA)

While for a three-core cable, the dielectric losses can be calculated using the equation (5)

$$P_{D_3} = 3 \cdot P_{D_1} \ \left[\text{Watt}\right] \quad (5)$$

There are several models that can be used in analyzing the transmission and distribution lines. Transmission or distribution lines can be modeled based on the value of its capacitive leakage current. This value is influenced by several things, including the length of lines, the system voltage level, and the distance conductor to ground (earth).

For a small capacitance value, it can be ignored. This usually occurs in over head lines that are less than 80 km (short-line model). Meanwhile, if the capacitance values ismedium, it must be included in the analysis. There are two models that could be done, first by assuming that the capacitance is distributed equally on both ends of lines (model "phi" = Π). Alternatively, it assumed to be unity at the center of the lines (Model "T"). It usually called the medium line model, which is the overhead distribution lines system with length ≤ 240 km. Meanwhile, if capacitance value is large, the value of distributed capacitance should be analyzed along the line. In the overhead lines, usually it is called a model of long line (> 240 km) [9, 10].

2. SYSTEM ANALYSIS

Distribution lines medium-voltage underground cables that join the TLB - MTQ, installed 80-100 cm under the surface of the road. Track is used is to trace the roadside of TanjungRhu, Dr. Sutomo, Hang Tuah, Pattimura, and General Sudirman streets. The single-line diagram is as shown in Figure 6.

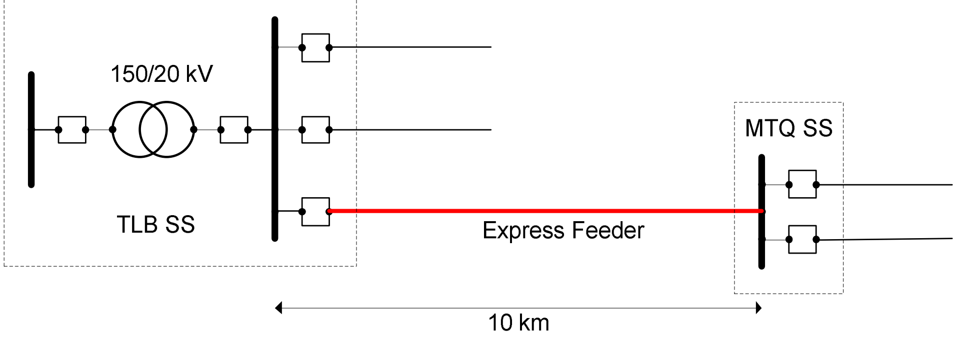


Figure 6. One line diagram Distribution Line TelukLembu Substation – MTQ Substation.

Express Feeder is 10 km in length using an aluminum conductor XLPE insulation right (Cross Linked Poly Ethylene) of the type NA2XSEFGbY measuring 3 x 240 mm^2. Feeders finally managed by PT. PLN (Persero) Region SimpangTiga, whichreceived supply from the TelukLembusubstation (SS), using underground cable distribution line 20 kV [11]. XLPE insulated cable has the dielectric loss lower than on other types of insulation such as PVC (Polyvinyl chloride) and EPR (Ethylene Propylene Rubber) [4, 12].

Furthermore the voltage and current profiles are obtained at TelukLembu SS, based on hours of operation on December 6, 2010. The data is as shown in Table 3. From the table, it is shown that the peak load begins at 18:00 hours until 21:00 pm. Where the maximum load occurs at phase 'T' at 19:00, with the average peak load is equal to 237.66 Ampere. The additionalsubstantial load occurs during hours of 17:00 to 18:00 pm. The increase reached 17%, where at 17:00 the new average weight of 190.66 Ampere with a voltage of 20.3 kV Amperes, while at 18.00 pm rose to 224.33 Ampere. The minimum peak load occurred at 06.00 am, with the largest decrease occurred in the period from 9:00 p.m. to 22:00 pm.

Table 3 also shows that, the maximum peak voltage occurs at 18.00 pm, which is 20,600 Volts. As been seen, the peak voltage occurs when the load average is quite large (224.33 Ampere). The minimum peak voltage of 19,200 Volt occurred at 1:00 pm. The other thing is at 1:00 to 2:00, system voltage is less the 20 kV. It could be a period before where interruption in these lines will take place.

Table 3. Express Feeder TLB – MTQ Profile

Time	MTQ Exp Feeder Current (A)			Volt (V)
	Phase R	Phase S	Phase T	
01:00	167	167	178	19,200
02:00	165	165	175	19,900
03:00	160	160	172	20,100
04:00	157	157	168	20,200
05:00	155	155	165	20,200
06:00	150	150	160	20,300
07:00	154	153	163	20,500
08:00	170	176	174	20,000
09:00	170	177	173	20,000
10:00	176	179	178	20,200
11:00	182	187	185	20,200
12:00	180	179	181	20,300
13:00	178	186	183	20,500
14:00	187	195	191	20,200
15:00	190	197	196	20,300
16:00	185	186	194	20,300
17:00	187	187	198	20,300
18:00	220	219	234	20,600
19:00	233	233	247	20,100
20:00	231	231	245	20,200
21:00	220	220	235	20,200
22:00	195	196	196	20,100
23:00	199	182	187	20,100
24:00	193	192	190	20,200

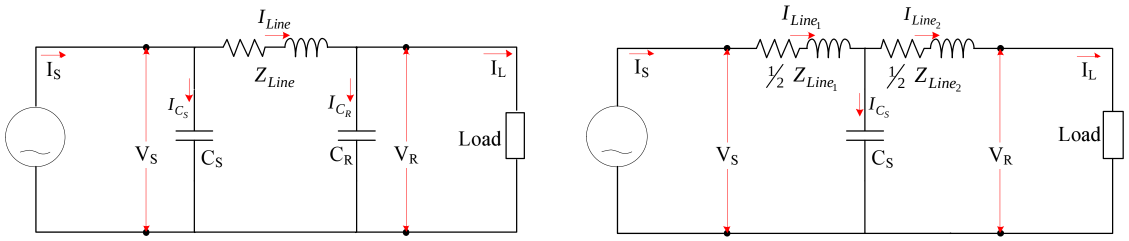
Table 4. MTQ SS Load Data

Time	Outgoing Line (Amp)		Incoming Line (Amp)		Volt (kV)
17:00	L1	195	L1	192	20,500
	L2	201	L2	200	
	L3	200	L3	196	
18:00	L1	211	L1	206	20,700
	L2	217	L2	213	
	L3	216	L3	212	
19:00	L1	249	L1	245	20,100
	L2	252	L2	251	
	L3	255	L3	254	
20:00	L1	240	L1	236	20,800
	L2	242	L2	239	
	L3	245	L3	242	
21:00	L1	236	L1	233	20,400
	L2	240	L2	239	
	L3	242	L3	241	

3. RESEARCH METHOD

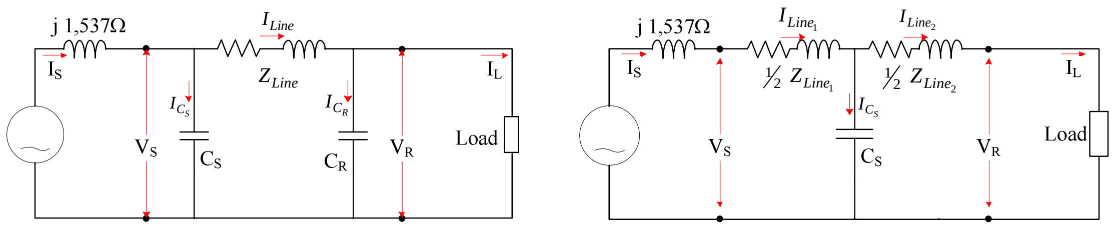
The method used in analyzing underground cable distribution system which is 10 km long, uses two circuit models: (1) nominal "pi" (π) circuit, and (2) nominal "T" circuit. At the nominal "pi" (π) circuit, it is assumed that the capacitance is evenly distributed along the cable,the model is divided equally on both ends of lines, while the inductive impedance is in the middle of lines. Figure 7.a. shows that the C_S and C_R are the capacitance of the lines which is at the sending and the receiving end. For the nominal "T" circuit, it is assumed that the capacitance is evenly distributed along the wire, modeled as a capacitance which is at the center of the lines, while the inductive impedance is modeled equally divided on both ends of lines. Both model of theses circuit are as shown in Figure 7.

The use of underground cables resulted in the existence of capacitance effects in the system. In this system, the power factor is 0.9 leading. Therefore, it is necessary to have an inductive reactive power compensation. Considering the system is a capacitive reactive power, it needs to be installed inductive reactive power. So that's why, inductor as a supplier of inductive reactive power should be installed.



(a). Nominal Phi "Π" (b). Nominal T

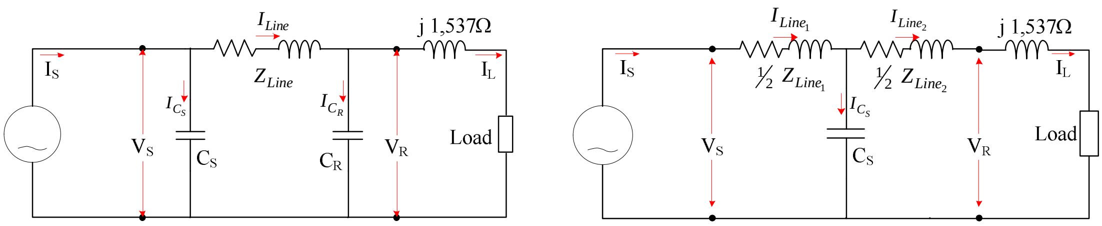
Figure 7. GI TelukLembu – GH MTQ Distribution Line model



(a). Nominal Phi "Π" (b). Nominal T

Figure 8. Inductor installed at the sending end or TelukLembu Substation

This analysis is conducted with the addition of the inductor with 2 (two) scenarios. First scenario is to place or install the inductor at the sending or the TLB SubStation side. Then do the analysis of the system. The circuit is as shown in Figure 8. The second scenario is to place or install the inductor on the receiving end or MTQ substation side. The circuit is as shown in Figure 9. Afterwards an inductive reactive power requirement of the system is calculated. Then using that data, the similar analysis using scenario 1 and scenario 2 is conducted. The calculation is done with the help of Matrix Laboratory software (MatLab). The calculation is performed at every hour, from 01:00 hours until 24.00 pm.



(a). Nominal Phi "Π" (b). Nominal T

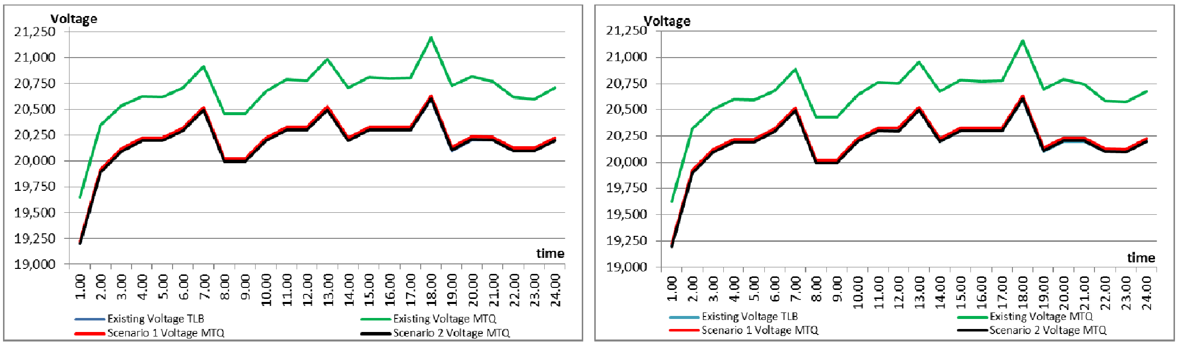
Figure 9. Inductor installed at the sending end or MTQ Substation

4. RESULTS AND ANALYSIS

The results of the analysis conducted on the third circuit of Figures 7, 8 and 9 are as shown in Table 5.

4.1. Exsisting Condition

Under these conditions is seen that the average voltage on the GH MTQ 2.43% is larger than its sending end (TLB SS). The total capacitive leakage current that occurs during the 24 hours is 249.61 Ampere. The dielectric loss that occurred in line is equal to 3.53 MW. Assuming a month is 30 days and the profile of the system every day for a month is similar, then its losses amounted to 105.98 MW per month.



(a). Nominal “Phi” Π (b). Nominal “T”

Figure 10. Voltage graph profiles that occur in three condition

Table 5. Voltage and current profiles before and after the installation of Inductor

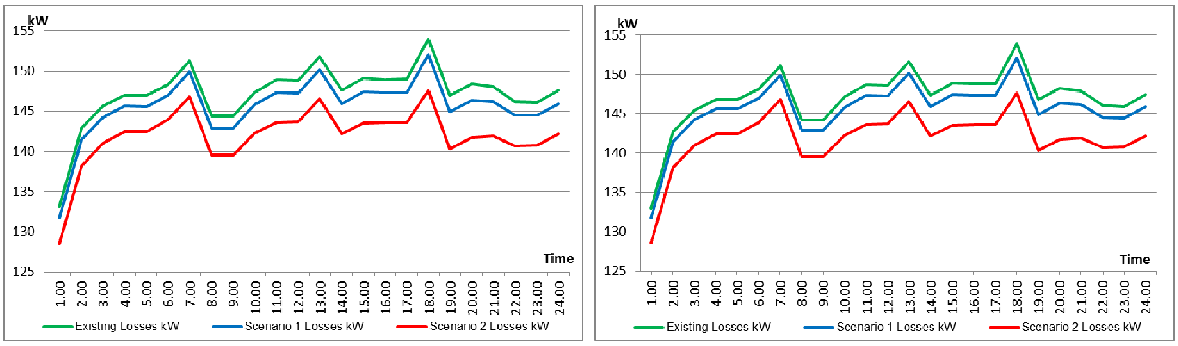
Time	Existing Condition				Inductor at TLB			Inductor at MTQ		
	Voltage		ArusBocor [A]	Dielec Loss [kWh]	Voltage MTQ [Volt]	ArusBocor [A]	Rugi2 saluran [kWh]	Voltage MTQ [Volt]	ArusBocor [A]	Dielec Loss [kWh]
	TLB [Volt]	MTQ [Volt]								
01:00	19200	19,625.27	9.89	132.96	19,223.46	9.85	131.73	19,196.67	9.72	128.53
02:00	19900	20,318.84	10.24	142.67	19,922.73	10.21	141.43	19,894.98	10.08	138.15
03:00	20100	20,507.61	10.34	145.45	20,121.85	10.31	144.23	20,093.83	10.18	141.00
04:00	20200	20,599.00	10.39	146.82	20,221.19	10.36	145.63	20,193.03	10.24	142.44
05:00	20200	20,593.02	10.39	146.78	20,220.76	10.36	145.60	20,192.61	10.24	142.47
06:00	20300	20,680.14	10.44	148.13	20,319.80	10.40	146.99	20,291.51	10.29	143.93
07:00	20500	20,888.56	10.54	151.09	20,520.33	10.51	149.92	20,491.76	10.39	146.77
08:00	20000	20,431.60	10.30	144.19	20,023.61	10.26	142.89	19,995.72	10.13	139.51
09:00	20000	20,431.60	10.30	144.19	20,023.61	10.26	142.89	19,995.72	10.13	139.51
10:00	20200	20,642.58	10.40	147.13	20,224.33	10.36	145.79	20,196.15	10.23	142.29
11:00	20300	20,760.46	10.46	148.71	20,325.58	10.42	147.30	20,297.25	10.28	143.64
12:00	20300	20,750.20	10.46	148.63	20,324.84	10.42	147.26	20,296.52	10.28	143.68
13:00	20500	20,954.35	10.56	151.57	20,525.07	10.52	150.18	20,496.47	10.38	146.53
14:00	20200	20,676.75	10.41	147.38	20,226.79	10.37	145.92	20,198.60	10.23	142.16
15:00	20300	20,785.23	10.46	148.89	20,327.36	10.42	147.39	20,299.03	10.28	143.55
16:00	20300	20,769.85	10.46	148.78	20,326.26	10.42	147.34	20,297.93	10.28	143.61
17:00	20300	20,775.83	10.46	148.82	20,326.69	10.42	147.36	20,298.35	10.28	143.59
18:00	20600	21,161.94	10.64	153.83	20,632.77	10.59	152.04	20,603.99	10.42	147.57
19:00	20100	20,696.43	10.39	146.81	20,135.44	10.34	144.93	20,107.34	10.16	140.32
20:00	20200	20,791.24	10.44	148.21	20,235.03	10.39	146.34	20,206.79	10.21	141.75
21:00	20200	20,743.39	10.43	147.86	20,231.59	10.38	146.17	20,203.36	10.22	141.92
22:00	20100	20,588.78	10.36	146.03	20,127.69	10.32	144.53	20,099.63	10.17	140.71
23:00	20100	20,572.54	10.36	145.91	20,126.53	10.32	144.47	20,098.47	10.18	140.77
24:00	20200	20,678.46	10.41	147.39	20,226.91	10.37	145.93	20,198.72	10.23	142.16

4.2. Scenario1

The inductor is placed at the sending end or TLB SS (see Figure 10). This configuration is created for the improvement of the system. The voltage at the receiving end (MTQ) decreased on the average of 2.25% than before installing the inductor, or only up to 0.13% from the sending end. While the total capacitive leakage current is also decreased by 1.06% to 248.55 Ampere, where previously 249.61 Ampere. This also resulted in lower power losses is reduced to 3.49 MW. With the same assumptions of similar profile for a month, then the power loss will decrease 1.16 MW (model Phi) and 1.02 MW (model “T”).

4.3. Scenario 2

Meanwhile, for the second scenario, the results obtained are better than the first scenario. The average voltage at the receiving end is almost the same as the sending end, which is on average is lower by 0.01%. Capacitive leakage current decreased to 245.17 Ampere only. This resulted in dielectric losses in the line dropped to 126.25 kW, compared with the existing conditions, of 3.41 MW. Furthermore, when compared to scenario 1, the losseswas reduced to 87.69 kW. With the same assumptions (similar every day for a month), then the losses per month could be save from 3.79 MW (3.57%) for model Phi and 3.65 MW (3.45%) for model “T”.



(a). Nominal “Phi” Π (b). Nominal “T”

Figure 11. Graph of power loss that occurs during the 24 hours

Moreover, using both scenarios,it can be seen that the selection of the location of the installation or placement of the inductor location also affects the performance of the system. Both the first and second scenarios are have shown improvement in the system. However, result obtained when using the second scenario is much better. This can be seen from the voltage at the receiving end, leak current capacitive and line losses which are decreased.

Hence, by using the second scenario it will produce a technically better system. In addition, the PT. PLN (Persero) will be able to save the technical losses occurs on their systems. By using almost the same cost, certainly the second scenario is a better choice since the results are significantly better.

Table 6. Comparison of Losses Model "Phi" and the Model T before and after the installation of Inductor

Description	Model Phi [kW]	Model T [kW]
Dielectric losses per day before installing inductor	3,532.78	3,528.23
Dielectric losses per dayafter installing inductor at sending end	3,494.23	3,494.27
Saving losses	38.55	33.96
Saving for a month	1,156.57	1,018.91
Dielectric losses per dayafter installing inductor at receiving end	3,406.51	3,406.54
Saving losses	126.27	121.69
Saving for a month	3,788.24	3,650.60

5. CONCLUSION

Based on the description above it can be seen that the second scenario is much better than the first scenario, where the position of the inductor is placed at the receiving or the MTQ SS. It can save losses of PT. PLN (Persero) per month of 3.788 MW (3.57%) for model Phi and 3.65 MW (3.45%) for model “T”. When compared with the first scenario just save of 1.16 MW (1.09%) only per month for model Phi and 1.02 MW (0.9 %) for model “T”.

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