Article

Study of Hybrid Transmission HVAC/HVDC by Particle Swarm Optimization (PSO)

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Abstract: Indonesia's SUMBAGUT 150 kV transmission of High Voltage Alternating Current Network (HVAC) system has considerable power losses. These power losses are a critical problem in the transmission network system. Meanwhile, this study provides one solution to reduce power losses using a High Voltage Direct Current (HVDC) network system. Determining the location to convert HVAC into HVDC is very important. The authors use Particle Swarm Optimization (PSO) to get the optimal location on the 150 kV SUMBAGUT HVAC transmission network system. The study results showed that before using the HVDC network system, the power losses were 122.26 MW. Meanwhile, power losses with one transmission HVDC in the "Paya Pasir-Sei Rotan" are 84.16 MW, "Porsa-P. Siantar" 90.83 MW, "Paya Pasir-Paya Geli" 104.14 MW. Then power losses with two transmission HVDC in "Paya Pasir-Sei Rattan" and "Porsa-P. Siantar" is 71.24 MW, "Paya Pasir-Sei Rotan" and "Paya Pasir-Paya Geli" 77.46 MW, "Porsa-P. Siantar" and "Paya Pasir-Paya Geli" 78.52 MW. The last result, power losses with three transmission HVDC in "Paya Pasir-Sei Rotan," "Porsa-P. Siantar," and "Paya Pasir-Paya Geli" lost 64.57 MW.

Keywords: high voltage alternating current; high voltage direct current; particle swarm optimization; power losses

1. Introduction

The transmission system is a system that functions to transmit electricity from the generator to the main power substation. Therefore, the transmission system must be able to deliver good electrical power. Transmission lines are generally in the form of open conductors whose channel lengths are up to tens of kilometers. It will result in short circuit and voltage stability. There are two types of transmission in the transmission system: High Voltage Alternating Current (HVAC) [1], High Voltage Direct Current (HVDC) [2], and Hybrid HVAC/HVDC systems [3].

In HVDC transmission, some things must be considered, namely the existence of an HVDC converter substation. Alternating current (AC) from the substation is sent to a converter rectifier. AC electric power is converted into direct current (DC) electric power. Thus, the rectifier converter's output is direct current (DC) electric power transmitted through the overhead line or cable to the rectifier-inverter. Furthermore, DC electric power is converted back into AC for industry or households. The HVDC Line Commutated Converter (HVDC LCC) is in the HVDC transmission system. HVDC LCC is a converter that uses thyristors and transistors. HVDC LCC uses a current source to conduct/activate thyristors [4-6].

In Indonesia, the State Electricity Company (PLN) uses HVAC transmission to distribute electricity from the generator to the distribution network. However, the HVAC transmission has some problems at very long distances. One of the problems is the transmission system will experience a power loss along the line due to the length of the conductor. Based on the abovementioned problems, this research applies an HVDC transmission system without changing the HVAC system. HVDC is efficient at 500 km and above [7, 8]. Previous studies found that the HVAC/HVDC transmission system is the best and most effective choice for overcoming problems on the transmission side of electric power [9, 10].

Using an HVAC/HVDC hybrid transmission system can be a solution to reduce losses on the transmission side, especially in transmission systems that initially use an HVAC transmission system. Several previous studies have been carried out to implement the HVAC/HVDC hybrid transmission system, such as "Comparative Evaluation of the HVDC and HVAC Links Integrated into a Large Offshore Wind Farm (An Actual Case Study in Taiwan)". It concludes that the HVDC transmission system will not interfere with the performance of the HVAC transmission system to obtain maximum performance between the two transmission systems [11]. "New Adaptive Controller in a Two Area HVAC/HVDC Power System" concludes that using a new controller can improve the HVAC/HVDC hybrid transmission system [12]. "Analytical Modeling Of HVDC-HVAC Systems" concluded that the HVDC/HVAC system has been analytically proven reliable [13]. " Comparative study of HVAC and HVDC transmission systems" concluded that the HVDC transmission system has less power loss than HVAC, with a difference of 1.4529% at a transmission distance of 100 km and 11.905% difference at a transmission distance of 1000 km [14]. Based on several studies above, the authors make models and simulations if the HVAC/HVDC hybrid transmission system is realized into the HVAC 150 kV transmission system in SUMBAGUT Indonesia with the Particle Swarm Optimization (PSO) method. This study aims to find out which transmissions are feasible to replace with HVDC transmission systems, aiming to achieve a transmission system that can reduce losses as small as possible. The power flow analysis method in multiple bus systems will be analyzed using the Newton-Raphson method because it has better calculations for larger power systems.

2. Materials and Methods

2.1. Materials

Single line diagram of SUMBAGUT 150kV, as shown in Figure 1. Further, in the simulation of the 150 kV SUMBAGUT power system, there are a total of 72 buses, of which 1 bus is a slack bus, 14 buses are generator buses (PV), and 57 buses are load buses (PQ) [15]. The classification of the type of bus used for the simulation can be seen in Table 1.

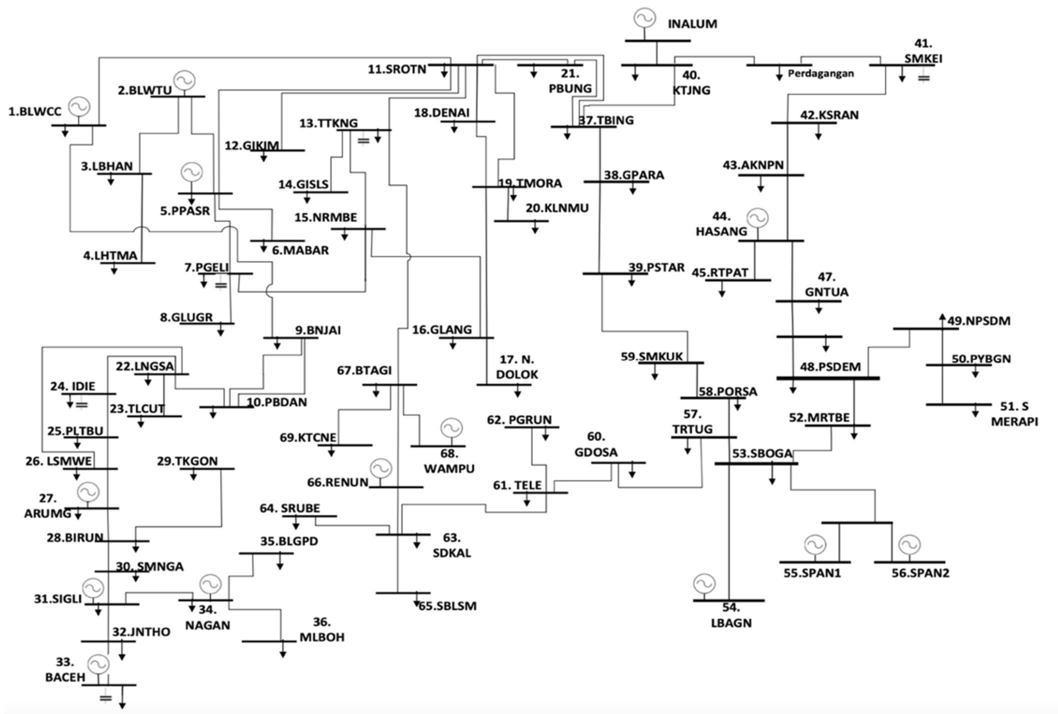

Figure 1. Single line diagram of SUMBAGUT 150kV.

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Table 1. Classification of Bus Types SUMBAGUT 150kV.

Bus Type	Bus Name	Number of Buses
Slack Bus	BLWCC	1
Bus Generator	BLWTU, PPASR, ARUMG, SIGLI, BACEH, NAGAN, KTJNG, HASANG, LBAGN, SPAN1, SPAN2, RENUN, WAMPU, TPSIL dan TPNIL.	15
Bus Beban	LBHAN, LHTMA, MABAR, PGELI, GLUGR, BNJAI, PBDN, SROTN, GIKIM, TTKNG, GISLS, NRMBE, GLANG, N.DOLOK, DENAI, TMORA, KLNMU, PBUNG, LNGSA, TLCUT, IDIE, PLTBU, LSMWE, BIRUN, TKGON, SMNGA, JNTHO, BLGPD, MLBOH, TBING, GPARA, PSTAR, SMKEI, KSRAN, AKNPN, RTPAT, KTPNG, GNTUA, PSDEM, NPSDM, PYBGN, SORIK MERAPI, MRTBE, SBOGA, TRTUG, PORSA, SMKUK, GDOSA, TELE, PGRUN, SDKAL, SRUBE, SBLSM, BTAGI, SRULA dan KTCNE.	56
	Amount	**72**

2.2. Methods

In an alternating current (AC) system, it is easy to increase and decrease the voltage by using a transformer. Direct current distribution systems have advantages over alternating current systems, including simpler isolation, high efficiency, and no stability problems. An illustration of the HVDC transmission network can be seen in Figure 2 [16, 17].

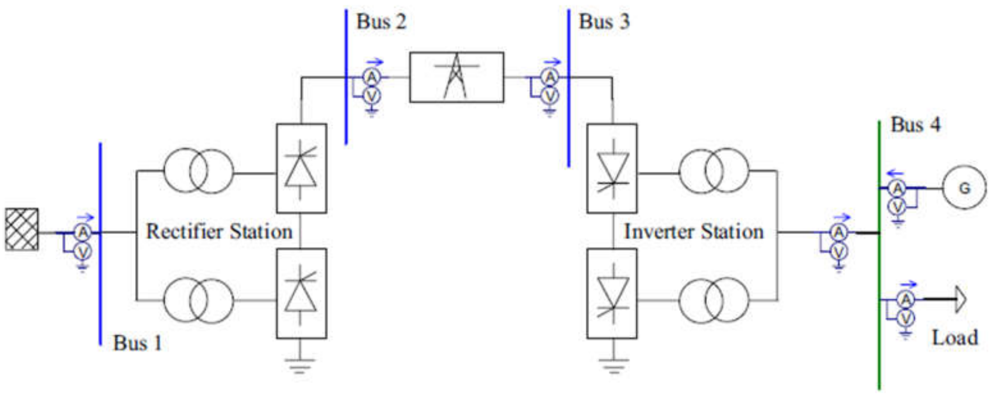

Figure 2. HVDC Transmission Network.

The following equation is determined by the converter transformer rating on the HVDC transmission system.

$$S_{transformer\ rectifier} = \sqrt{2}.I_n\,.V_{in\ rectifier} \quad (1)$$

$$S_{transformer\ inverter} = \sqrt{2}.I_n\,.V_{in\ inverter} \quad (2)$$

In these equations, the following variables were used : $S_{transformer\ rectifier}$, $S_{transformer\ inverter}$ total power of transformer rectifier / inverter (MVA), I_n input current (Amp), $V_{in\ rectifier}$, $V_{in\ inverter}$ voltage transformer in rectifier / inverter.

Hundreds or thousands of kilometers generally separate electrical systems between generating and load centers, so the electricity generated must be transmitted through transmission line wires. Distributing electricity has several problems, one of which is power losses or losses. Power losses occur due to several factors, namely corona factors, insulator leakage, distance, and others. Power loss can be known if the voltage at the base of the sender (generating) and the base of the receiver are different [18-20].

$$Vr = \frac{\sqrt{3}.\rho.L.I.Cos\ phi}{A} \quad (3)$$

$$P_{rugi} = I^2.R \quad (4)$$

$$\%P_L = \frac{P_{L1}-P_{L2}}{P_{L1}}.100\% \quad (5)$$

In these equations, the following variables were used : V_r Voltage Drop (V), ρ specific resistance ($\Omega\ m$), L length of conducting cable (m), A cross-sectional area $V_{in\ inverter}$ voltage transformer, P power loss (kW), P current on the load side, R resistance of the conductor, $\%P_L$ efficiency value of power losses (%), P_{L1} value of initial power losses (MW), P_{L2} value of final power losses (MW).

3. Results

3.1. Transmission System Power Flow SUMBAGUT 150 kV (HVAC)

The value of power losses in the SUMBAGUT 150 kV transmission system without changing the HVAC/HVDC hybrid transmission system is 68.41 MW. Meanwhile, eight voltage profiles are outside the SPLN standard (0.9 V 1.05), as seen in Figure 3.

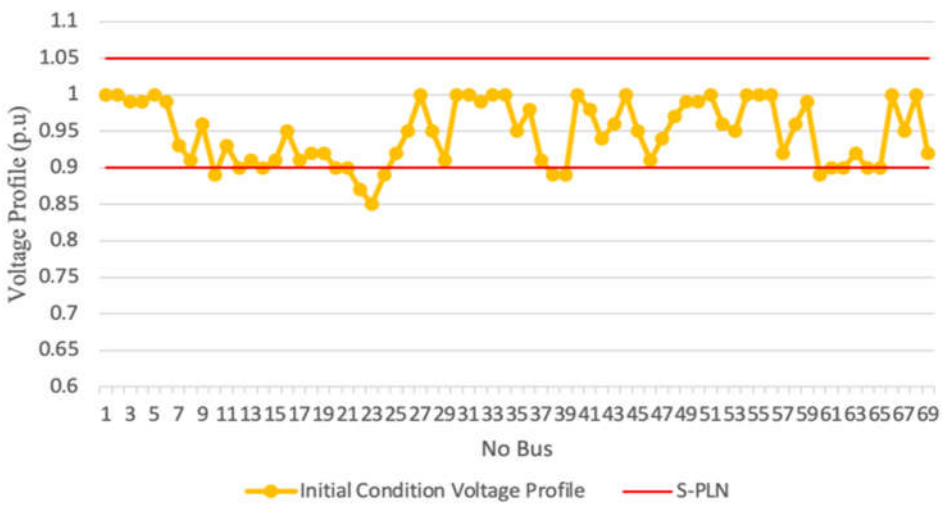

Figure 3. Voltage profile of SUMBAGUT 150 kV transmission system without changing the HVAC/HVDC hybrid transmission system.

3.2. Determination and Placement of HVDC Transmission Locations

After analyzing the power flow and running the Particle Swarm Optimization (PSO) program, we got the three best transmission locations to convert HVAC transmission into hybrid HVAC/HVDC. These transmissions are the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) transmission line is 21 km, the 150 kV Paya Pasir (bus 5) - Sei Rotan (Bus 11) transmission line is 24 km, and the 150 kV Renun (Bus 66) - Sidikalang (Bus 63) transmission line is 25 km with each transmission loss of 5462 kW, 5348 kW, and 5098 kW, respectively. From the data above, the Paya Geli (Bus 7) with a total load of 114.84 MVA, the Sei Rotan (Bus 11) with a total load of 50.69 MVA, and the Sidikalang (Bus 63) bus with a total load of 49.39 MVA. Here, the HVAC/HVDC hybrid system plays an important role as a better power conductor than HVAC.

Previously, to determine the power of the rectifier-inverter transformer, we used the formulas in (1) and (2). Calculation of the rectifier-inverter transformer rating on the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) line.

$$S_{transformer\ rectifier} = \sqrt{2}.In.V_{in\ rectifier}$$

$$S_{transformer\ rectifier} = \sqrt{2}\ x\ 0.85\ x\ 150 = 179.77\ MVA$$

$$S_{transformer\ inverter} = \sqrt{2}.In.V_{in\ inverter}$$

$$S_{transformer\ inverter} = \sqrt{2}\ x\ 0.85\ x\ 150 = 179.77\ MVA$$

So, the rectifier-inverter transformer rating on the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) line is 179.77 MVA, as shown in Figure 4.

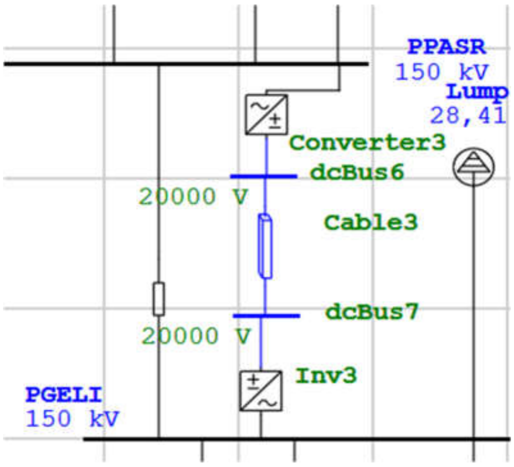

Figure 4. Placement of the HVDC Transmission System in Paya Pasir (Bus 5) - Paya Geli (Bus 7).

Calculation of the rectifier-inverter transformer rating on the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) line.

$$S\ transformer\ rectifier = \sqrt{2}.In.Vsec\ Rec$$

$$S\ transformer\ rectifier = \sqrt{2}\ x\ 0.96\ x\ 150 = 203.4\ MVA$$

$$S\ transformer\ inverter = \sqrt{2}.In.Vsec\ Inv$$

$$S\ transformer\ inverter = \sqrt{2}\ x\ 0.96\ x\ 150 = 203.4\ MVA$$

Thus, the rating of the rectifier-inverter transformer on the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) line is 203.4 MVA, as seen in Figure 5.

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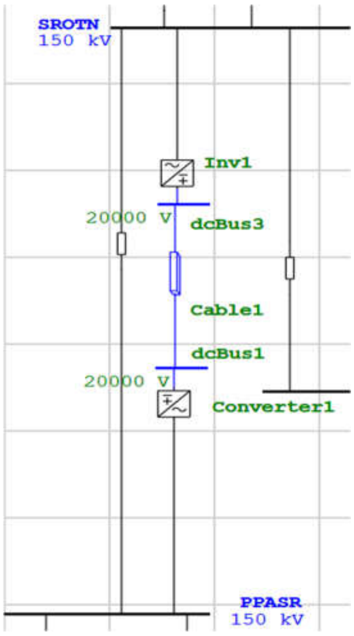

Figure 5. Placement of the HVDC Transmission System in Paya Pasir (Bus 5) - Sei Rotan (Bus 11).

Calculation of the rectifier-inverter transformer rating on the 150 kV Paya Pasir (Bus 5) - Sidikalang (Bus 63) line.

$$S\ transformer\ rectifier\ =\ \sqrt{2}.In\ .Vsec\ Rec$$

$$S\ transformer\ rectifier\ =\ \sqrt{2}\ x\ 0.63\ x\ 150\ =133.64\ MVA$$

$$S\ transformer\ inverter\ =\ \sqrt{2}.In\ .Vsec\ Inv$$

$$S\ transformer\ inverter\ =\ \sqrt{2}\ x\ 0.63\ x\ 150\ =133.64\ MVA$$

Thus, the rating of the rectifier-inverter transformer on the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) line is 133.64 MVA, as described in Figure 6.

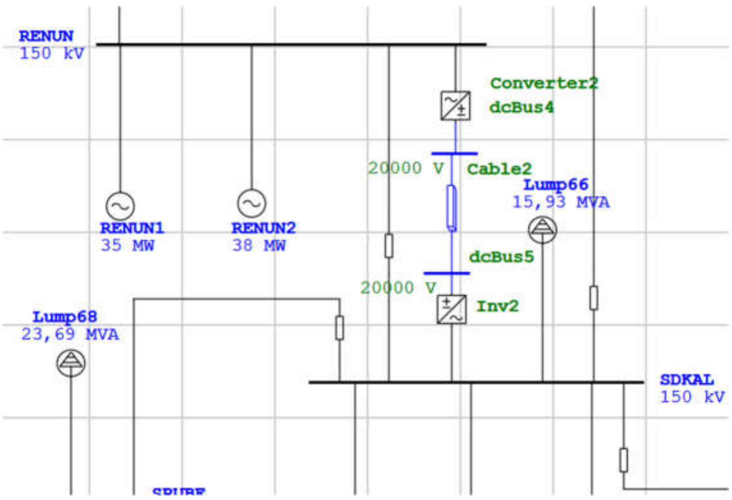

Figure 6. Placement of the HVDC Transmission System in Renun (Bus 66) – Sidikalang (Bus 63).

After getting the rectifier-inverter transformer rating, the transmission line voltage is lowered to 20 kV on the HVDC line through the rectifier and returned to 150 kV again after passing through the inverter.

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3.3. Transmission HVDC of Power Flow SUMBAGUT 150 kV

The number of channels converted to hybrid HVAC/HVDC in the SUMBAGUT transmission system is three and produces seven combinations for comparison.

3.3.1. Paya Pasir (Bus 5) - Paya Geli (Bus 7)

The simulation results from converting the 150 kV Paya Pasir (Bus 5) – Paya Geli (Bus 7) line into HVDC transmission obtained SUMBAGUT transmission losses of 57.31 MW. The value of the efficiency of power losses before and after the conversion we get with the equation 5.

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 57.31}{68.41}.100\% = 16.22\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) - Paya Geli (Bus 7) has an overall power loss reduction efficiency of 16.22%. Meanwhile, the voltage profile, as shown in Figure 7.

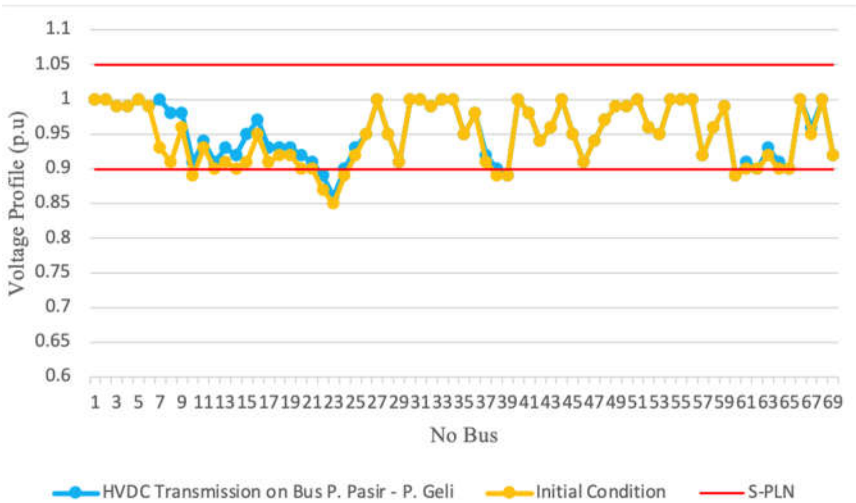

Figure 7. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Paya Pasir (Bus 5) - Paya Geli (Bus 7).

3.3.2. Paya Pasir (Bus 5) – Sei Rotan (Bus 11)

The simulation results from converting the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) line into HVDC transmission obtained SUMBAGUT transmission losses of 51.79 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 5.

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 57.79}{68.41}.100\% = 24.29\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) – Sei Rotan (Bus 11) has an overall power loss reduction efficiency of 24.29%. Meanwhile, the voltage profile, as shown in Figure 8.

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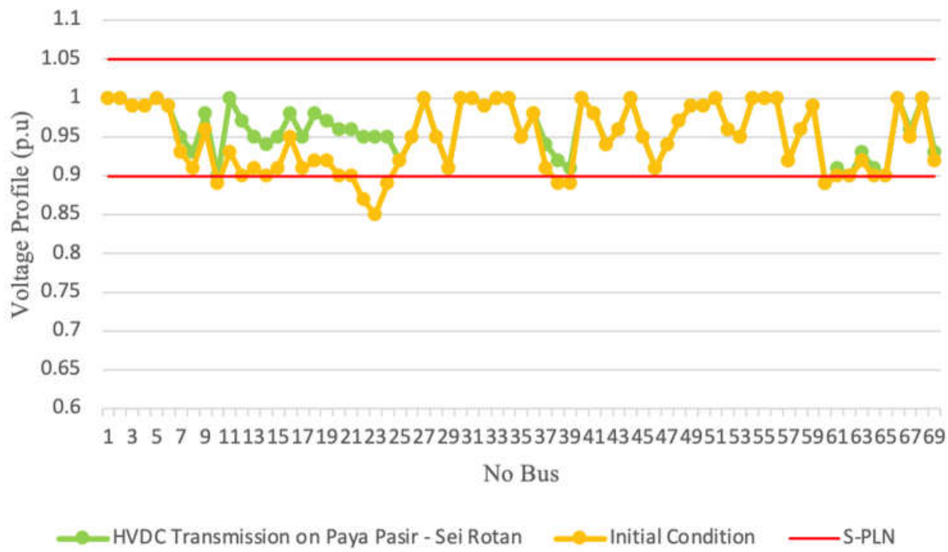

Figure 8. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Paya Pasir (Bus 5) – Sei Rotan (Bus 11).

3.3.3. Renun (Bus 66) – Sidikalang (Bus 63)

The simulation results from converting the 150 kV Renun (Bus 66) – Sidikalang (Bus 63) line into HVDC transmission obtained SUMBAGUT transmission losses of 60.80 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 5.

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 60.8}{68.41}.100\% = 11.12\%$$

Thus, the result of converting the 150 kV SUMBAGUT Renun (Bus 66) – Sidikalang (Bus 63) has an overall power loss reduction efficiency of 11.12%. Meanwhile, the voltage profile, as shown in Figure 9.

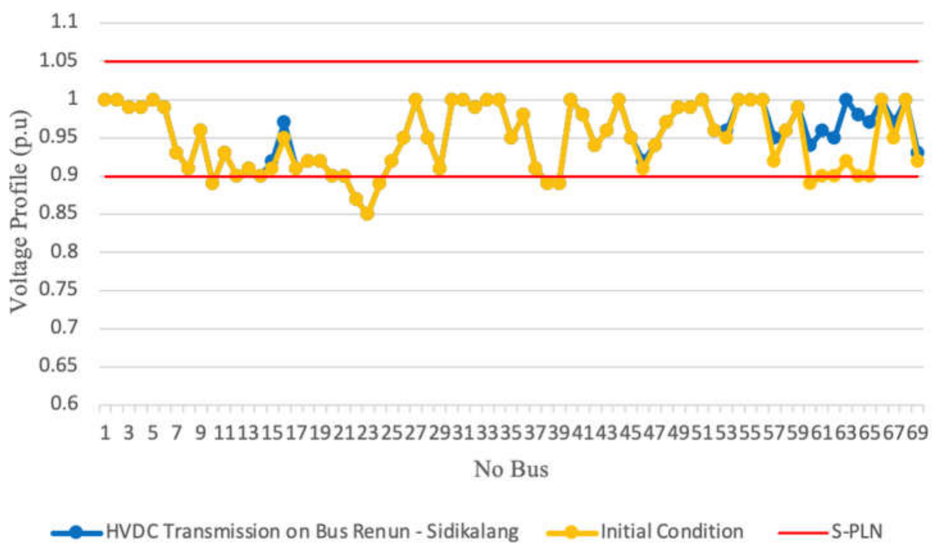

Figure 9. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Renun (Bus 66) – Sidikalang (Bus 63).

3.3.4. Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Paya Pasir (Bus 5) - Sei Rotan (Bus 11)

The simulation results from converting the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Paya Pasir (Bus 5) - Sei Rotan (bus 11) line into HVDC transmission obtained SUMBAGUT transmission losses of 45.70 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 2.21

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 45.7}{68.41}.100\% = 33.19\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Paya Pasir (Bus 5) - Sei Rotan (Bus 11) has an overall power loss reduction efficiency of 33.19%. Meanwhile, the voltage profile, as shown in Figure 10.

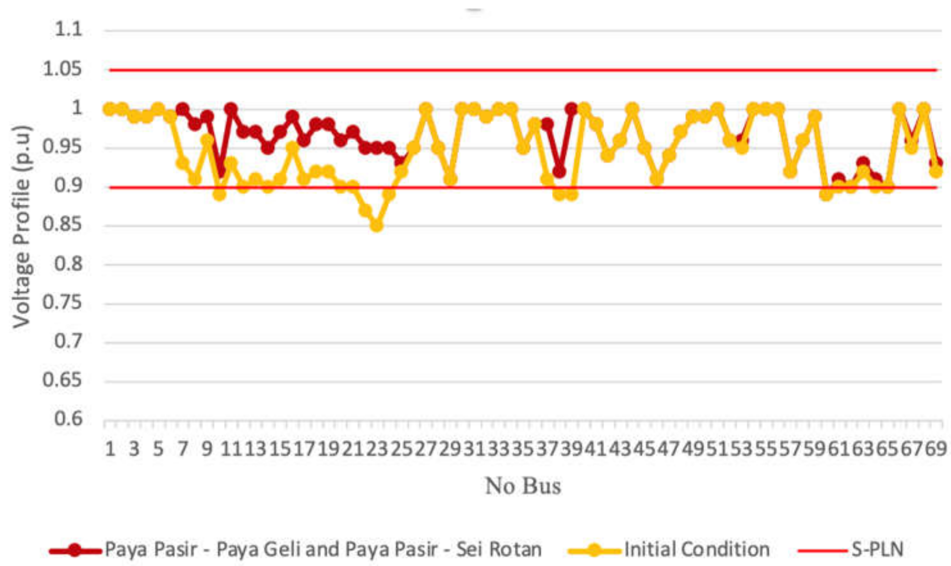

Figure 10. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Paya Pasir (Bus 5) - Sei Rotan (Bus 11).

3.3.5. Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Renun (Bus 66) – Sidikalang (Bus 63)

The simulation results from converting the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Renun (Bus 66) - Sidikalang (Bus 63) line into HVDC transmission obtained SUMBAGUT transmission losses of 49.95 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 5.

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 49.95}{68.41}.100\% = 26.98\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Renun (Bus 66) – Sidikalang (Bus 63) has an overall power loss reduction efficiency of 26.98%. Meanwhile, the voltage profile, as shown in Figure 11.

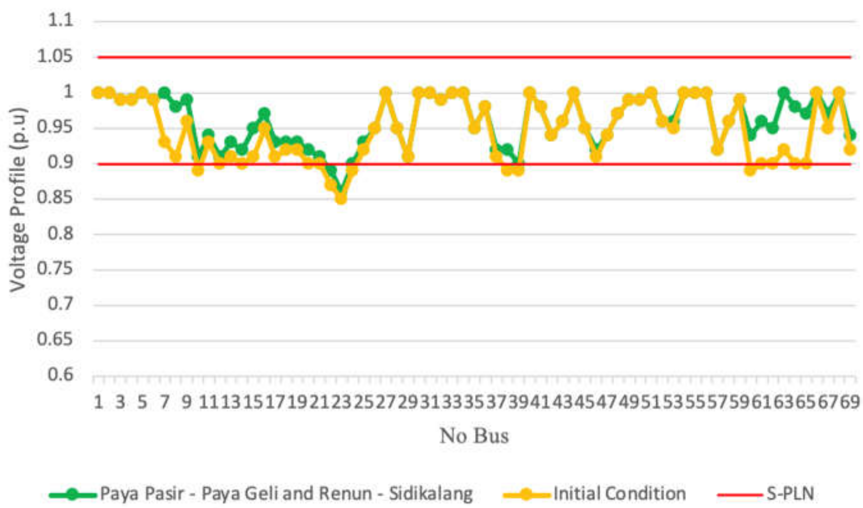

Figure 11. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Paya Pasir (Bus 5) - Paya Geli (bus 7) and Renun (Bus 66) – Sidikalang (Bus 63).

3.3.6. Paya Pasir (Bus 5) - Sei Rotan (Bus 11) and Renun (Bus 66) – Sidikalang (Bus 63).

The simulation results from converting the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) and Renun (Bus 66) – Sidikalang (Bus 63) line into HVDC transmission obtained SUMBAGUT transmission losses of 44.69 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 2.21

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 44.69}{68.41}.100\% = 34.67\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) - Sei Rotan (Bus 11) and Renun (Bus 66) – Sidikalang (Bus 63) has an overall power loss reduction efficiency of 34.67%. Meanwhile, the voltage profile, as shown in Figure 12.

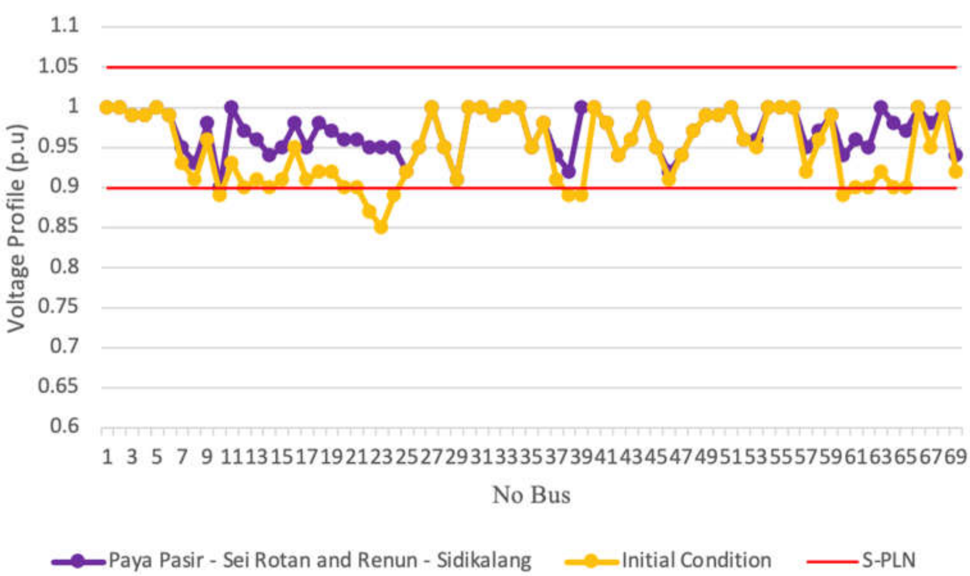

Figure 12. Voltage profile of SUMBAGUT 150 kV transmission system with changing the HVDC transmission system in Paya Pasir (Bus 5) - Sei Rotan (Bus 11) and Renun (Bus 66) – Sidikalang (Bus 63).

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3.3.7. Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rotan (Bus 11), and Renun (Bus 66) – Sidikalang (Bus 63)

The simulation results from converting the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rotan (Bus 11), and Renun (Bus 66) - Sidikalang (Bus 63) line into HVDC transmission obtained SUMBAGUT transmission losses of 38.71 MW.

The value of the efficiency of power losses before and after the conversion we get with the equation 2.21

$$\%P_L = \frac{P_{L1} - P_{L2}}{P_{L1}}.100\%$$

$$\%P_L = \frac{68.41 - 38.71}{68.41}.100\% = 43.41\%$$

Thus, the result of converting the 150 kV SUMBAGUT Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rotan (Bus 11), and Renun (Bus 66) - Sidikalang (Bus 63) has an overall power loss reduction efficiency of 43.41%.

4. Discussion

Based on the results, changing the HVDC transmission is a better choice for use, especially in the Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rattan (Bus 11), and Renun (bus 66) – Sidikalang (Bus 63) transmission, as seen in Table 4.4.

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Transmission	Power Losses (MW)	Efficiency (%)
Initial Condition	68.41	-
Paya Pasir (Bus 5) - Paya Geli (Bus 7)	57.31	16.22
Paya Pasir (Bus 5) - Sei Rotan (Bus 11)	51.79	24.29
Renun (Bus 66) – Sidikalang (Bus 63)	60.8	11.12
Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Paya Pasir (Bus 5) - Sei Rotan (Bus 11)	45.7	33.19
Paya Pasir (Bus 5) - Paya Geli (Bus 7) and Renun (Bus 66) – Sidikalang (Bus 63)	49.95	26.98
Paya Pasir (Bus 5) - Sei Rotan (Bus 11) and Renun (Bus 66) – Sidikalang (Bus 63)	44.69	34.67
Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rotan (Bus 11), and Renun (Bus 66) – Sidikalang (Bus 63)	38.71	43.41

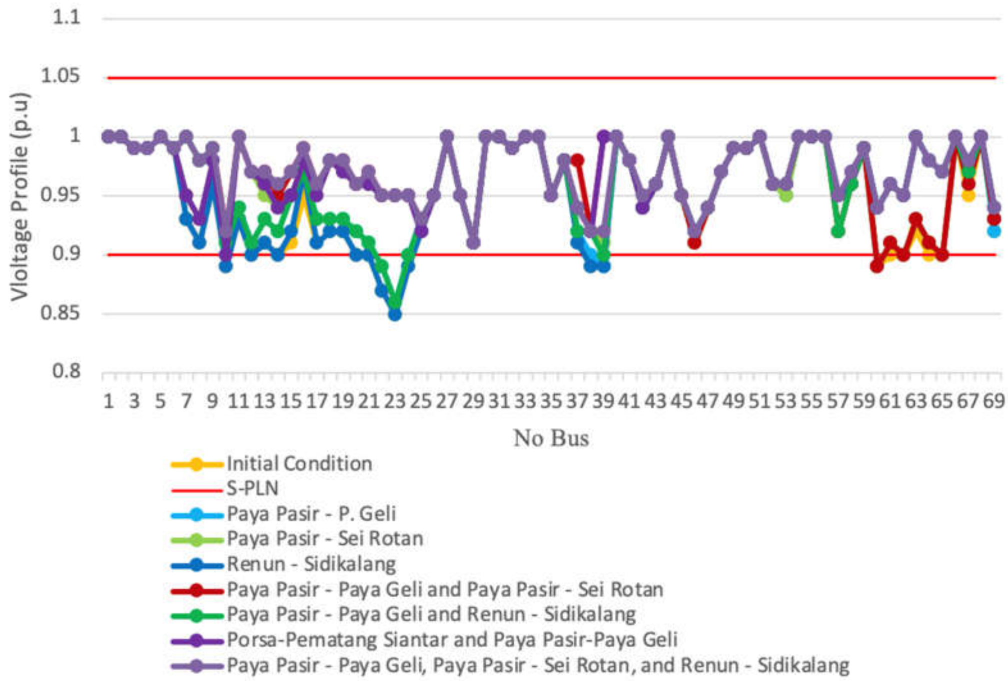

Figure 13. Voltage profile of SUMBAGUT 150 kV transmission system in all conditions.

5. Conclusions

Based on the research in this research, the following conclusions are obtained:

- The best line locations to convert to hybrid HVAC/HVDC are the 150 kV Paya Pasir (Bus 5) - Paya Geli (Bus 7) transmission line is 21 km, the 150 kV Paya Pasir (Bus 5) - Sei Rotan (Bus 11) transmission line is 24 km, and the 150 kV Renun (Bus 66) – Sidikalang (bus 63) transmission line is 25 km with each channel losses of 5462 kW, 5348 kW, and 5098 kW.
- The best combination of channels results in combining these three channels into a hybrid HVAC/HVDC. The 150 kV channel conversion of Paya Pasir (Bus 5) - Paya Geli (Bus 7), Paya Pasir (Bus 5) - Sei Rotan (Bus 11), and Renun (Bus 66) – Sidikalang (Bus 63) is the result of the best channel conversion with a total loss of the entire SUMBAGUT transmission system of 38.71 MW with a decreasing percentage of 43.41%.

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Data Availability Statement: The data are available from the corresponding author upon request.

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Conflicts of Interest: The authors declare no conflict of interest.

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