Minimization of Transmission Loss in Application of HVDC Networks under Load Increase Scenario

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***Abstract*—This study aims to analyze the effect of embedding HVDC (High Voltage Direct Current) on the voltage stability and power losses of the system. Sequential power flow is used to execute the combined AC-DC power flow by adjusting the estimation of DC slack bus injection to speed up convergence and to get more optimal results. Several systematic load increase scenarios are proposed in this study to provide stress loading on the system so that the performance of HVDC can be evaluated. This simulation was implemented on the IEEE 14-Bus System and IEEE 57-Bus System.**

***Index Terms*—AC-DC system, HVDC networks, power loss, steady-state, Voltage Source Converter (VSC)**

I. Introduction

In a power system, the transmission network holds an essential role in connecting interaction from the power plant to the distribution side [1]. Therefore, the operation and planning of the transmission network should be designed in an effective manner [2]. The operation of High Voltage Alternating Current (HVAC) systems have been used since 100 years ago and very mature in transmitting large amounts of electrical energy [3]. However, there are some limitations of conventional HVAC transmission systems which are lower reliability in delivering electrical energy, environmental factors, efficiency, power losses, construction costs, and the most crucial thing is related to the voltage stability of the system [4]-[10]. In a power system, voltage stability has been considered as an important requirement for a power system to operate safely and reliably [11], [12] because a large amount of failures is caused by voltage instability [13]. The major problems that occur due to voltage stability are caused by immense losses of power transmitted in long-distance transmission lines [14] which is the weakness of the HVAC system. Therefore, the need for increased transmission capability as well as reduced plant operation to a minimum [15]-[17] has led to the use of High Voltage Direct Current (HVDC) to improve the quality and reliability of AC system networks [3]. This is due to the advantage of the HVDC system which covers the shortcomings of the AC systems [3], [5], [6], [8]-[10], [18].

The integration of HVDC into the HVAC network produces a new power flow that is more complex because the components involved are not only the AC component but also the DC component so that the resulting equation is a combined equation of AC and DC power flow [19]. The analysis of this combined power flow has gained renewed importance with the emergence of Voltage Source Converter (VSC), the most recent technology of HVDC, which requires an efficient power flow method to get an effective operation and control [20], [21]. For solving the power flow in this area, there exist two different approaches that are the sequential approach [22], [23], and the unified approach [24], [25]. The sequential approach is more considered in this paper due to the convenient integration of the DC side equation into AC power flow without making any modification to the existing framework.

To improve the convergence, researchers provide diverse approaches in utilizing the sequential power flow. Some different control strategies are applied to the sequential power flow in [23] to form a Jacobian matrix associated with each operation mode. Reference [26] has put forward a convergence factor to diminish the iterations for each inner loop. An in-depth analysis of the divergence of the sequential method under heavy DC power was given in [27]. Nonetheless, these studies are more difficult and complex to be implemented.

Some load scenarios are also taken into consideration in this simulation to evaluate the voltage stability and power loss of the system. Load incremental scenario in STATCOM application which was proposed in [28] shows the capability of the device to improve the voltage stability. However, it is less efficient due to more than one device is needed. Furthermore, load increases simulation in the integration of the HVDC network in [29] results in decreased power loss. Nevertheless, it only provides an increase in active power load, whereas the increase in reactive power which also affects power losses is not considered.

Therefore, this paper provides a systematic load increasing scheme which is examined through a simple

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sequential power flow that uses the active power injection estimation control technique on the DC slack bus to accelerate convergence and get better results. This simulation is easy to be implemented under a novel load increase pattern involving VSC HVDC and will be evaluated on the standard IEEE-14 bus system and IEEE-57 bus system.

II. Proposed Methodology

A. Power Flow Analysis

Power flow analysis (PFA) [30] is the core of most power system planning studies and also the starting point for studies of transient and dynamic stability [31]. Power flow is needed for planning, design, operation, and economic dispatch in a power system [28], [31]. The key information of PFA [32], [33] is to find the value of the active and reactive power flowing through each transmission along with voltage magnitude and phase angle on each bus. This process becomes more challenging, more difficult, and more complex when HVDC is embedded in the system. It is because of the additional number of factors that affects the complexity of the computation, that are:

- Addition of auxiliary buses to the system.
- Inclusion of HVDC impedance into the impedance matrix.
- Inclusion of power contributed by HVDC into power flow mismatch equation.
- Formation of entirely new Jacobian Matrix formation.

To make it simpler and easier for the application, this research is only focused on the HVDC steady-state conditions.

B. Converter Model of HVDC System

The VSC converter has a role as a controllable voltage source with the Pulse-Width Modulation (PWM) switching method. By this method, the VSC converter can modulate the magnitude and phase angle of the output voltage. Fig. 1 shows the equivalent circuit model of the VSC converter, where Y_c is the complex admittance of the phase reactor; V_f, δ_f, and B_f are the voltage magnitude, phase angle, and susceptance of the filtering bus respectively; Y_{tf} is the complex admittance of the converter transformer; $V_{AC,i}$ and $\delta_{AC,i}$ are the magnitude and phase angle of the voltage of AC bus i respectively. As for the DC side, $I_{DC,i}$ is the current flow of the DC bus i.

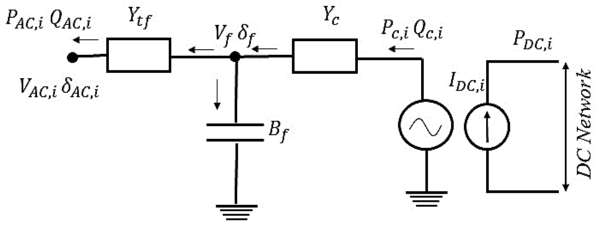

Fig. 1. Equivalent circuit model of VSC station [34].

The overall description of the power flow to the network is described in Fig. 2. Fig. 2 shows the detail of the AC/DC hybrid system which produces power flow to the network, where P_c and Q_c are the injected active and reactive power by VSC converter at the AC terminal respectively; P_{VSC_DC} is the injected power by VSC converter at the DC terminal, and P_{VSC_AC} and Q_{VSC_AC} are the active and reactive power injected by VSC into the AC network after passing the phase reactor and converter transformer respectively. Meanwhile, at the PCC (Point of Common Coupling) bus, the output of P_{VSC_AC} and Q_{VSC_AC} can be controlled by regulating the AC current through the phase reactor. This can be done by the appropriate modulation of the VSC converter.

The power coming out of the PCC bus will pass through the admittance of the AC line $Y_{AC,im}$ which connecting the AC bus i and m. Finally, after passing the admittance $Y_{AC,im}$, the active and reactive power will reach the AC bus i which are denoted by $P_{AC,i}$ and $Q_{AC,i}$ respectively. As for the DC network, after passing the admittance of the DC line $Y_{DC,im}$, the active power will reach the DC bus i which is denoted by $P_{DC,i}$.

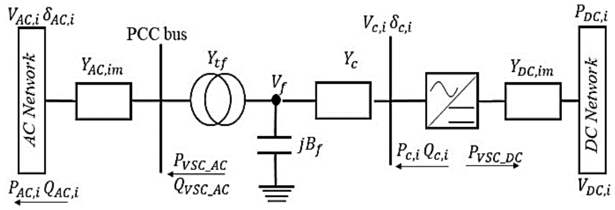

Fig. 2. Converter and AC-DC hybrid system [27]

The general power flow equations for this network are as follows:

1) AC side equations

The active and reactive power injected by VSC into the AC network through the converter transformer are shown by P_{VSC_AC} and Q_{VSC_AC}, respectively, and can be described as [23]:

$$P_{VSC\_AC} = -V_{AC}^2 G_{tf} + V_{AC} V_f \left[G_{tf} \cos(\delta_{AC} - \delta_f) + B_{tf} \sin(\delta_{AC} - \delta_f) \right] \quad (1)$$

$$Q_{VSC\_AC} = V_{AC}^2 B_{tf} + V_{AC} V_f \left[G_{tf} \sin(\delta_{AC} - \delta_f) - B_{tf} \cos(\delta_{AC} - \delta_f) \right] \quad (2)$$

where $Y_{tf} = G_{tf} + jB_{tf}$ with G_{tf} and B_{tf} are the conductance and susceptance of the converter transformer respectively, the index j shows the imaginary value of the complex variable which in this case the admittance Y_{tf}. As for δ_f is the voltage angle of the filtering bus.

2) Converter side equations

With a known value of the complex voltage of the converter AC terminal side V_c and filter bus V_f the power flow equation on the converter side are [35]:

$$P_c = V_c^2 G_c - V_f V_c \left[G_c \cos(\delta_f - \delta_c) - B_c \sin(\delta_f - \delta_c) \right] \quad (3)$$

$$Q_c = -V_c^2 B_c + V_f V_c \left[G_c \sin(\delta_f - \delta_c) + B_c \cos(\delta_f - \delta_c) \right] \quad (4)$$

where $Y_c = G_c + jB_c$ with G_c and B_c are the conductance and susceptance of the phase reactor respectively, and δ_c and δ_f are the voltage angle of the converter AC terminal side and filter bus respectively.

3) DC side equations

DC system modeling can be represented by a resistive network with the injection of DC currents and voltages at the other node of the converter [36], [37]. The current injected and the DC active power flow equation can be written as follows [21], [22]:

$$I_{\mathrm{DC}_i} = Y_{\mathrm{DC}_{im}}\left(V_{\mathrm{DC}_i} - V_{\mathrm{DC}_m}\right) \tag{5}$$

$$P_{\mathrm{DC}_i} = pV_{\mathrm{DC}_i}Y_{\mathrm{DC}_{im}}\left(V_{\mathrm{DC}_i} - V_{\mathrm{DC}_m}\right) \tag{6}$$

where $\boldsymbol{Y}_{\mathrm{DC}_{ij}}$ equals to $\frac{\mathbf{1}}{\boldsymbol{R}_{\mathrm{DC}_{ij}}}$; $\boldsymbol{R}_{\mathrm{DC}_{ij}}$ is the resistance of DC line $\boldsymbol{i-m}$; $\boldsymbol{V}_{\mathrm{DC}_i}$ and $\boldsymbol{V}_{\mathrm{DC}_m}$ are the voltage of the DC bus $\boldsymbol{i}$ and $\boldsymbol{m}$ respectively, meanwhile, p=1 is used for monopolar configuration and p=2 for bipolar configuration.

4) Converter losses

The model of converter losses of this study is a simplified type where converter losses vary quadratically with the phase reactor current magnitude. With the known voltage of the PCC bus which has the same value as the initial voltage of the AC bus V_{AC} and the power of the converter AC terminal side $S_c = P_c + jQ_c$, so the current of the converter I_c can be written as follows [20]:

$$\boldsymbol{I_c} = \frac{\boldsymbol{S_c}}{\boldsymbol{V_{AC}}} \tag{7}$$

And converter power loss P_{Loss} is [9], [20], [22], [35]

$$P_{\mathrm{Loss}} = a + b \cdot abs(I_c) + c \cdot abs(I_c)^2 \tag{8}$$

C. Sequential Power Flow

The sequential power flow is a method of solving the AC and DC combined power flow which are simulated separately, not in one iteration. The advantage of this method is that the DC equation is easy to integrate into the AC power flow equation without changing the existing system framework [21]. For clarity, the sequential power flow method is described in Fig. 3 which has been followed with some minor modification of what is presented in [35]. In this study, we assume that the estimated DC slack active power will affect the convergence and the final result. A power rating that is too high will affect the value of the converter current in (7) which will flow on the PCC side and will later affect the P_{Loss} in (8). This agrees with what was stated in the reference [38]. So that in this study the control of the DC slack bus power estimation is adjusted to the correct reactive power and commutation reactance settings to get the best results. The equation for the power flow of all buses except for the slack bus in the AC network can be written as [9], [20], [22], [35]:

$$P_{AC,i}(V_{AC}, \delta_{AC}) = V_{AC,i}\sum_{m=1}^{n} V_{AC,m}\left[G_{AC,im}\cos\left(\delta_{AC,i} - \delta_{AC,m}\right) + B_{AC,im}\sin\left(\delta_{AC,i} - \delta_{AC,m}\right)\right] \tag{9}$$

$$Q_{AC,i}(V_{AC}, \delta_{AC}) = V_{AC,i}\sum_{m=1}^{n} V_{AC,m}\left[G_{AC,im}\sin\left(\delta_{AC,i} - \delta_{AC,m}\right) + B_{AC,im}\cos\left(\delta_{AC,i} - \delta_{AC,m}\right)\right] \tag{10}$$

where $Y_{AC,im} = G_{AC,im} + jB_{AC,im}$ with $G_{AC,im}$ and $B_{AC,im}$ are the conductance and susceptance of the AC line respectively, and n is the total number of AC buses.

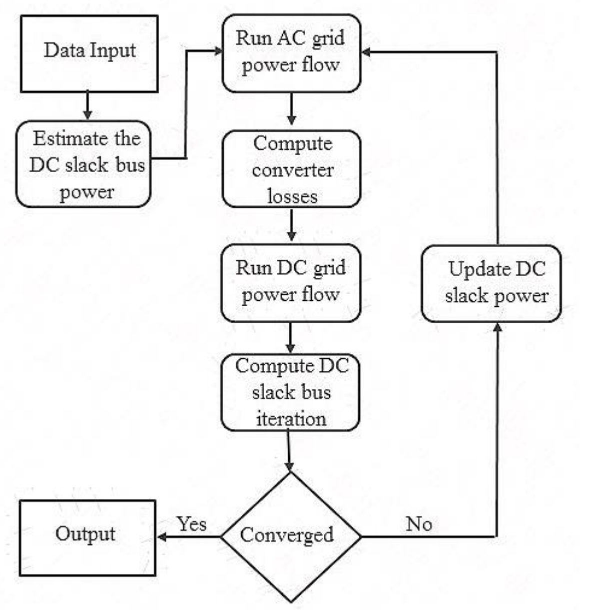

Fig. 3 Sequential power flow of VSC-HVDC [35].

For slack converter power P_{slack} on PCC is [21]:

$$P_{\mathrm{slack}} = V_{\mathrm{DC,slack}}\sum_{m=1}^{p} V_{\mathrm{DC}_m}Y_{\mathrm{DC,slack}_m} - P_{\mathrm{Loss,\,slack}} \tag{11}$$

where $V_{\mathrm{DC,slack}}$ is the voltage of DC slack bus; V_{DC_m} is the voltage of the DC bus m; $Y_{\mathrm{DC,slack}_m}$is the admittance of the line between DC slack bus and DC bus m, and $P_{\mathrm{Loss,slack}}$ is the power loss of the converter slack. By the power injected on this slack, the AC power flow can be simulated to get the voltage on the AC side. Newton-Raphson method is used to solve the nonlinear equation of AC power flow which is written as follows:

$$\Delta M_{AC} = -J_{AC}\Delta X_{AC} \tag{12}$$

where ΔX_{AC} is the incremental vector of the AC voltage and its phase angle, J_{AC} is the Jacobian matrix of AC network and ΔM_{AC} is the power mismatch equation at PCC bus which is defined as:

$$\Delta M_{\mathrm{AC}} = 0$$

$$P_{\mathrm{GD}_i} - P_{\mathrm{AC},_i} - P_{\mathrm{c},i} = 0 \tag{13}$$

$$Q_{\mathrm{GD}_i} - Q_{\mathrm{AC},_i} - Q_{\mathrm{c},i} = 0 \tag{14}$$

where $P_{\mathrm{GD}i}$ and $Q_{\mathrm{GD}i}$ is the power generated at bus i, $P_{\mathrm{AC},_i}$ and $Q_{\mathrm{AC},_i}$ can be obtained from (9) and (10), and $P_{\mathrm{c},i}$ and $Q_{\mathrm{c},i}$ are the active and reactive power generated at converter i. With the converter power loss already known from the (8) then the power is injected on the DC grid is:

$$P_{\mathrm{DC}_i} = P_{\mathrm{c},i} - P_{\mathrm{Loss}_i} \tag{15}$$

Newton Raphson method is used for solving the DC side equation which is defined as:

$$\Delta M_{\mathrm{DC}} = -J_{\mathrm{DC}}\Delta X_{\mathrm{DC}} \tag{16}$$

where ΔX_{DC} is the incremental vector of the DC voltage, J_{DC} is the Jacobian matrix of the DC network. And the mismatch equation of DC network ΔM_{DC} can be described as:

$$\Delta M_{\mathrm{DC}} = P_{\mathrm{DC}_i} - P_{\mathrm{c},i} - P_{\mathrm{Loss}_i} = 0 \tag{17}$$

III. Results and Discussions

In this paper, simulations are conducted to see how the HVDC performance in improving voltage stability. As the characteristics of the HVDC, the converter is capable of absorbing excess reactive power in the system which has an impact on reactive power and voltage on the AC system [15]. So that the simulation carried out in this study is to provide a systematically load-increasing pattern to stress the system to observe HVDC performance. The details of the proposed scenarios which is inspired by [28] are:

- Scenario 1: Active load change
- Scenario 2: Reactive load change
- Scenario 3: Active and reactive load change

These scenarios were implemented in the IEEE-14 Bus System and IEEE-57 Bus System.

1) Case IEEE-14 bus system

The case study of this research is shown in Fig. 4. To evaluate the power flows in a power system with HVDC with a systematic load-increasing scheme, the IEEE-14 Bus System has been modified by embedding the HVDC components. The placement of the HVDC is determined by running the power flow at the initial condition. From the results of the initial simulation, the highest network losses for the high voltage network are on Line 4 which connecting Bus 2 and Bus 3, so HVDC is placed on that line to minimize network losses.

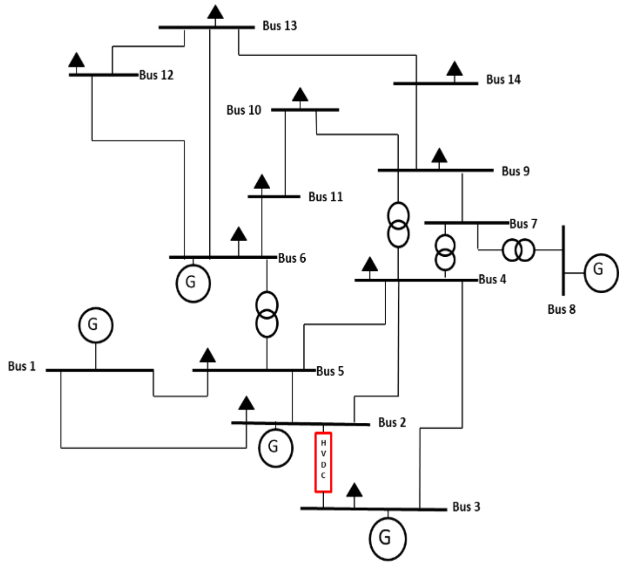

Fig. 4. IEEE-14 Bus System [39].

In this case, the increase of power load is based on a range from 1.9 p.u. to 9.5 p.u. of the baseload. The power load increment is selected from the highest load stress that can be carried by each bus. Before applying a change in load stress, a power flow simulation is first performed without installing HVDC so that results can be evaluated. Simulation results can be seen in Fig. 5.

However, based on Table I, surprisingly the voltage on Bus 3 has a very high voltage increase among all buses. This phenomenon is due to the installation of HVDC on Line 4. So the converter is set on Bus 3 and the inverter is set on Bus 2. As a result, as shown in Fig. 6, Bus 3 has the highest reactive power of all buses. This happens because of the presence of a rectifier that can adjust reactive power on Bus 3.

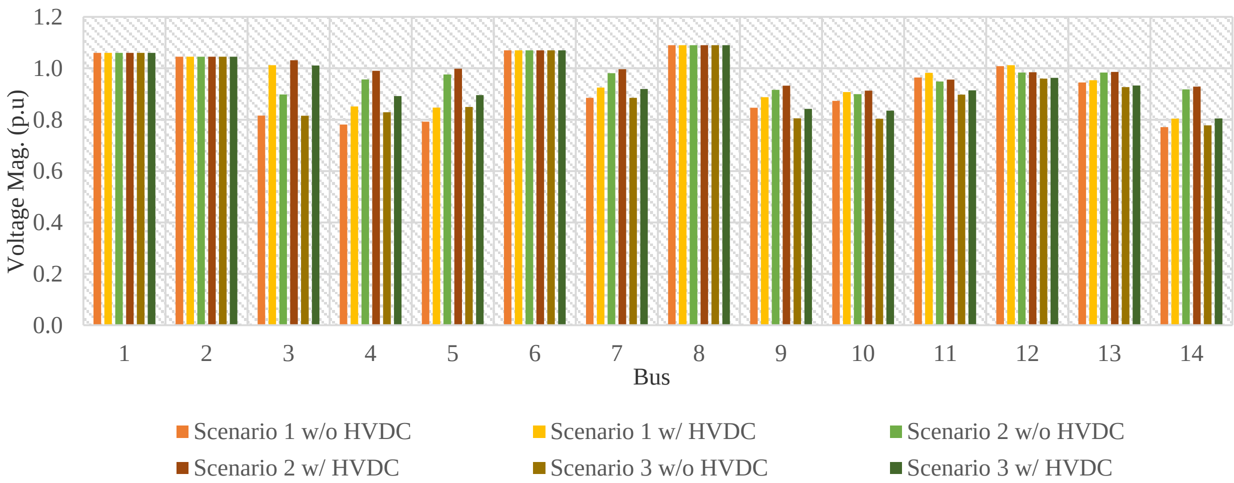

Fig. 5. Voltage magnitude profile (IEEE 14 -Bus).

TABLE I: Voltage Magnitude and Increase Voltage Percentage

Bus	Voltage								
	Scenario 1			Scenario 2			Scenario 3		
	w/o HVDC (p.u.)	w/ HVDC (p.u.)	% Vol. Inc.	w/o HVDC (p.u.)	w/ HVDC (p.u.)	% Vol. Inc.	w/o HVDC (p.u.)	w/ HVDC (p.u.)	% Vol. Inc.

1	1.060	1.060	0.000	1.060	1.060	0.000	1.060	1.060	0.000
2	1.045	1.045	0.000	1.045	1.045	0.000	1.045	1.045	0.000
3	0.816	1.012	24.01	0.898	1.031	14.80	0.815	1.011	23.95
4	0.781	0.852	9.048	0.957	0.991	3.536	0.829	0.892	7.539
5	0.792	0.847	6.904	0.976	0.998	2.261	0.850	0.896	5.446
6	1.070	1.070	0.000	1.070	1.070	0.000	1.070	1.070	0.000
7	0.885	0.925	4.484	0.981	0.997	1.635	0.885	0.919	3.837
8	1.090	1.090	0.000	1.090	1.090	0.000	1.090	1.090	0.000
9	0.846	0.887	4.858	0.916	0.932	1.776	0.806	0.842	4.499
10	0.873	0.908	3.942	0.899	0.913	1.559	0.804	0.835	3.923
11	0.964	0.982	1.845	0.949	0.956	0.786	0.898	0.915	1.879
12	1.008	1.012	0.400	0.984	0.985	0.135	0.960	0.963	0.353
13	0.945	0.953	0.881	0.983	0.986	0.262	0.927	0.933	0.726
14	0.771	0.804	4.296	0.918	0.928	1.159	0.778	0.805	3.412

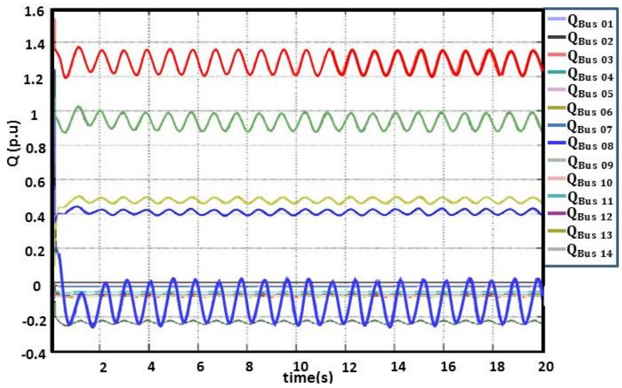

Fig. 6. Reactive power at all buses (Q).

Based on the description above, the capability of HVDC to control reactive power not only adjust the voltage of the bus but also the power flow on the line transmission. Therefore, with the appropriate control of line flow, power losses can be reduced. This loss reduction can be proven from the simulation conducted in Fig. 7. The graph shows the total network power losses for both active and reactive power are consistently reduced for each scenario.

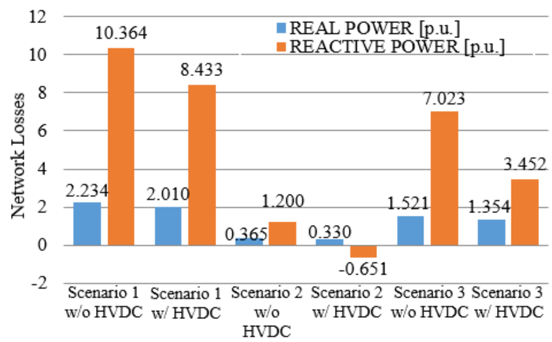

Fig. 7. Network losses.

1) Case IEEE-57 bus system

In this case, the IEEE 57 Bus is employed as a simulation object to validate the proposed method. Fig. 8 shows the standard IEEE 57-bus system which consists of 7 generators, 42 loads, 57 buses, 17 transformers, and 63 lines. The value and data of the IEEE 57-bus standard can be obtained in [40] and [41]. In this simulation, Scenario 1 provides an increase in active power by 20% of the baseload.

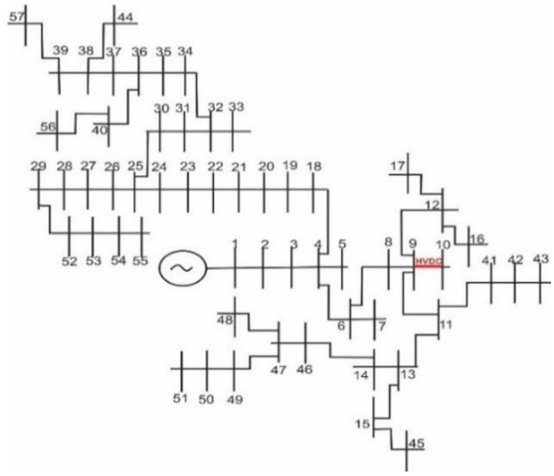

Fig. 8. IEEE-57 bus system [40].

Scenario 2 provides an additional reactive power of 35% of the baseload. And Scenario 3 is a combination of Scenario 1 and Scenario 2. The simulation results can be seen more clearly in Fig. 9.

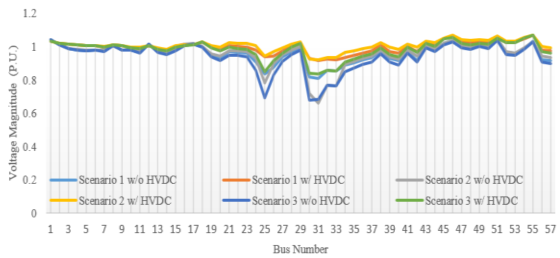

Fig. 9. Voltage magnitude profile for IEEE 57 bus in p.u.

From the results of the graph, there is an under-voltage, whose value is very far from the nominal value, which is around 0.66 p.u. on Bus 25 for Scenario 3 and Bus 30 for Scenario 2. This phenomenon also occurs in research [28] that applies the same scenario, but the buses that experience under-voltage are Buses 32-34. The voltage improvement that was carried out in the reference was the addition of STATCOM on Bus 31 and Bus 33. Although it was able to improve the voltage magnitude to 1.01 p.u. but this is considered inefficient because it has to add several devices to the network. In contrast to this research, by adjusting the proper control of power inject estimation, HVDC is able to improve the voltage for all buses and specifically for the voltage on Bus 25 and Bus 30. The voltage magnitude can be improved to 0.92 p.u

The reduction in power loss, in this case, can be seen in Fig. 10. The simulation results show a decrease in power loss in terms of both active and reactive power.

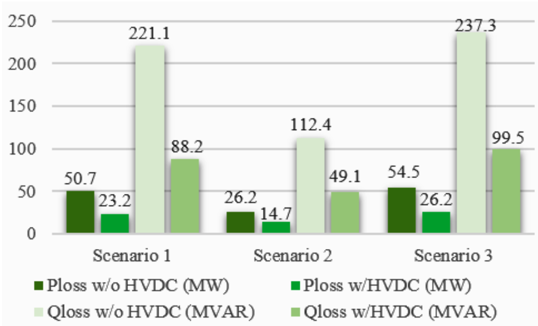

Fig. 10. Active and reactive power losses comparison of IEEE 57 bus system without and with HVDC.

TABLE II: POWER LOSS COMPARISON

Method	Location	Ploss (MW)		Qloss (MVAR)	
		Without HVDC	With HVDC	Without HVDC	With HVDC
Reference [29]	9-13	60.7	23.7	253.8	99.6
Proposed Method	9-10	50.766	23.234	221.12	88.18

The placement of HVDC in [29] using the GA heuristic method chose the line between 9-13 as the best location. However, in this simulation, we found that better results are obtained by embedding the HVDC between Bus 9 and Bus 10. This can be proven by what can be seen in Table II. The power losses for both active and reactive were successfully reduced.

In this reference, the scenario used is an increase in active power by 20%, so that only Scenario 1 is compared to this study. It can be seen that the control techniques mentioned in Section II show better results even when compared to the use of heuristic methods.

IV. CONCLUSION

Simple and systematic power flow has been simulated in this paper with HVDC as the object of research. The simulation is run based on the scheme of increasing load (Scenario 1, Scenario 2, and Scenario 3) to give stress to the system. And the results show that the installation of HVDC and controlling the estimation of DC slack power injection can reduce network losses and maintain the voltage on the AC system better and more efficiently.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Zulfiana conducted the research, analyzed data, and wrote the paper; Ardiaty acted as supervisor and advisor of the research and edited the paper; Yusri acted as supervisor and advisor of the research; all authors had approved the final version.

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