Load Flow Analysis for DER integrated AC/DC Distribution System affected by Converter and DC line Outages

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***Abstract*-- Conventional power networks has been running on AC power but development in power electronic devices demonstrates great potential for implementation of DC power networks. Numerous effects on employment of integrated AC/DC systems based on Voltage Source Converter (VSC) technology are underway. On the other hand, integration of DER in Distribution network emerged as a durable choice for fulfilling future energy need. The aim of this study is to perform the load flow analysis for Voltage Source Converter-Multi terminal (VSC-MTDC) based AC/DC Distribution system incorporated with DER. Employed DERs are Photovoltaic (PV) system, Wind Energy, Fuel cells and Gas Turbine Energy Generator. An IEEE 14 bus distribution network is modified to include VSC-MTDC network model for the implementation of Newton-Raphson load flow algorithm. This paper also introduces mathematical models for VSC and load flow to study the steady-state change in AC/DC network as a result of converter and DC line Outage due to faults.**

***Keywords*: AC/DC Distribution system, Load Flow Analysis, Distributed Energy Resources**

I. Introduction

FROM last few decades, the power engineers are facing a lot of challenges to fulfill the growing demand for electrical power energy of the world. The growing hunger for development in efficient and cost effective energy resources results in an increase in employment of DC distribution systems accompanying Distribution Energy Resources (DER). Recent developments in power electronics demonstrated a great potential of DC power networks; like reduction in distribution losses, low cost of distribution cables, high capacity of power supply and improved power quality [1], [2]. In Europe, plans to construct a whole new overlaying DC "Supergrid" are taking concrete form [3], [4]. Considering advantages of DC distribution network, meshed DC grid connected with AC infrastructure at various locations is providing more reliable solution. Special attention is given to DC grid based on Voltage Source Converter (VSC) technology for its advantages because of: (1) rapid growth in power electronics technology and (2) integrating renewable energy sources and energy storages devices with traditional AC grid [5]. In transition to approach for pure DC distribution network, use of integrated AC/DC distribution scheme is gradually gaining popularity.

DER on other hand emerged as a durable choice to deal with the growth in energy demand, minimizing environmental effects, increase efficiency and service reliability [6]. Massive integration of intermittent renewable energy resources into the grid may also impose major challenges in terms of secure grids integration and operation.

Recent studies demonstrate the analysis of steady-state behavior of integrated AC/DC Distribution systems. VSC-MTDC technology can support the integrated AC/DC system in many forms especially in fast and independent control of active and reactive power. Development in load flow algorithms for integrated AC/DC Distribution system implemented through VSC-MTDC system has made some achievements like considering VSC effects on load flow in [7], [8]. The main objective of this paper is to analyze the steady-state load flow algorithm for VSC-MTDC AC/DC distribution system integrated with DER. Secondly, the algorithm is extended to demonstrate the change in the steady state of VSC-MTDC system due to converter and DC line outages as a result of transient faults. In the event of converter and DC line outage, the power balance is affected in AC and DC grids.

This paper is structured as follows: Section II briefly describes the AC and DC grid modeling along with the steady-state VSC converter structure and loss associated with it. Section III presents the implementation of AC/DC load flow algorithm. Finally the section IV shows the simulation results for the load flow analysis of integrated AC/DC distribution system, and effects of converter and DC line outages on system steady-state using the open source Matlab toolbox, MATPOWER [9].

II. System Model

A. AC Grid and VSC Modeling

The most essential part for the integration of AC and DC grid linkage is the VSC converter. Fig. 1 shows the general model of Voltage Source Converter (VSC), which acts as controllable voltage source behind complex admittance [10]. This complex admittance can be distinguished among admittance of interface transformer $Y_{tf} = G_{tf} + jB_{tf}$, susceptance of low pass filter jB_f and admittance of phase reactors $Y_c = G_c + jB_c$. $\mathbf{U_{AC}} = U_{AC} \angle \delta_{AC}$ represents the voltage

This work was supported by Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20164030200980).

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Paper submitted to the International Conference on Power Systems Transients (IPST2017) in Seoul, Republic of Korea June 26-29, 2017.

output at AC bus, $\mathbf{U_c} = U_c \angle \delta_c$ expresses the output voltage at converter bus and U_{DC} is the DC bus output voltage. The connected filter voltage is represented by $\mathbf{U_f} = U_f \angle \delta_f$ and interface transformer voltage by $\mathbf{U_{tf}} = Ut_f \angle \delta_{tf}$.

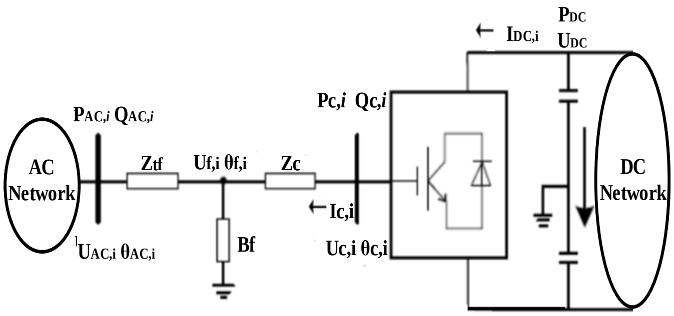

Fig. 1. Model of a VSC for AC/DC Grid

The power injected to AC system is represented by $P_{AC,i}$, $Q_{AC,i}$ and the power flowing to AC network from the converter side is $P_{c,i}$ and $Q_{c,i}$, while the DC power is shown by $P_{DC,i}$. The subscript *i* represent the AC and DC bus number. Following equations represent the active and reactive power of steady-state VSC converter model [11].

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

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

$$P_c = U_c^2 G_c - U_{AC} U_c \left[G_c \cos(\delta_{AC} - \delta_c) - B_c \sin(\delta_{AC} - \delta_c) \right] \quad (3)$$

$$Q_c = -U_c^2 B_c + U_{AC} U_c \left[G_c \sin(\delta_{AC} - \delta_c) + B_c \cos(\delta_{AC} - \delta_c) \right] \quad (4)$$

Where G_{tf} and G_c represents the conductance of interface transformer and converter respectively. Similarly, B_{tf} and B_c represents the susceptance of interface transformer and converter respectively.

B. Converter Control modes

VSC converter technology has the ability to control the active power P_{AC} and reactive power Q_{AC} injection with respect to the output voltage at AC-side independently. Because of this advantage in VSC technology, we can classify the control modes which can be categorized as follow [12]:

1) Constant P_{AC}-control: In this mode, the converter controls its constant active power injection P_{AC} into the AC grid.
2) Constant U_{DC}-control: In this mode, the converter controls its constant DC voltage U_{DC} by adjusting the active power injection P_{AC}.
3) Constant Q_{AC}-control: In this mode, the converter controls its constant reactive power injection Q_{AC} into the AC grid.
4) Constant U_{AC}-control: In this mode, the converter controls its constant AC bus Voltage U_{AC} by adjusting the reactive power injection Q_{AC}.

In VSC-MTDC system, one of the converter is modeled as "DC Slack Bus Converter". This converter is used to accommodate for the DC system losses and to keep up the voltage U_{DC} of DC grids. From the above-mentioned modes, the converter stations can be considered either as in PQ- or PV- control mode in AC grid with exception from converter associated with the DC Slack Bus Converter.

C. Converter Losses

In practice, the VSC losses are neglected and assumptions are made for the simplification of the analysis. It is important to consider converter losses, which add up to the total losses in VSC-MTDC network. A generalized loss model of VSC station incorporates the filter losses and phase reactor losses along with the drop in transformer impedance. A quadratic loss model is used in this analysis, in which the converter losses are derived as a function of magnitude of the reactor current I_c [13]. The reactor current magnitude depends upon the active and reactive power exchanged from converter to AC network. Whereas the total converter losses P_{loss} is the combination of three components referred as constant, linear and variable [14]. Circuit losses associated with the off-state of the device are descried as constant losses, while linear losses are associated with the switching losses related to current state. The generated heat loss and reverse recovery loss are considered as variable loss and are taken as the square of the current I_c. Mathematically I_c and P_{loss} can be represented by (5-6)

$$I_c = \frac{\sqrt{P_c^2 + Q_c^2}}{U_c \sqrt{3}} \quad (5)$$

$$P_{loss} = A + BI_c + CI_c^2 \quad (6)$$

Where *A*, *B* and *C* are the per unit loss coefficients which are determined by the test data of converter losses based on [13]. The values for loss coefficients are given in Table I and can be derived by taking into account a general converter loss model for typical VSC-HVDC link. The per unit loss coefficient data in this paper has been scaled down as per requirement for appropriate MVA rating of the system.

TABLE I
VSC CONVERTER DATA

Converter Loss Coefficient (p.u)		Converter Data	
A	0.01103	R_t (p.u)	0.0015
B	0.00887	X_t (p.u)	0.1121
C *(rectifier)*	0.02885	B_f (p.u)	0.045
C *(Inverter)*	0.04371	R_c (p.u)	0.0001
		X_c (p.u)	0.1642

D. DC Grid Modeling

By convention, it is considered in an AC network that the reactive power flow mainly associated with the magnitude of voltage at the different buses whereas the flow of active power linked to the angle difference between buses. However, in DC network, the reactive power is ignored, only active power is considered, and its flow depends upon the difference in voltage magnitude between the DC buses. In steady-state, the impedance in DC network can be represented as a lumped resistance only while omitting the line inductance and capacitance as it does not have any effect in power flow.

1) DC Grid Model

The DC network load flow exhibits many similarities to those of conventional AC network load flow. For DC network of ***n*** nodes, the conductance matrix G_{DC} can be represented as

$$G_{DC} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ G_{n1} & G_{n2} & \cdots & G_{nn} \end{bmatrix} \tag{7}$$

$$G_{DCii} = \sum_{\substack{i \neq j \\ j=1}}^{n} g_{ij}, G_{DCij} = -g_{ij}, i \neq j \tag{8}$$

Where $G_{DC\mathbf{ij}}$ represent the conductance between DC bus **i** and **j**. The combined currents injections of DC grid for all ***n*** buses can be written in matrix form as

$$I_{DC} = G_{DC} U_{DC} \tag{9}$$

$$I_{DC,i} = \sum_{\substack{j=1 \\ j \neq i}}^{n} G_{DC.ij} \left(U_{DC,i} - U_{DC,j} \right) \tag{10}$$

Here $\boldsymbol{U_{DC}} = [U_{DC1}, U_{DC2} \ldots U_{DCn}]^T$ and $\boldsymbol{I_{DC}} = [I_{DC1}, I_{DC2} \ldots I_{DCn}]^T$ represent DC voltage vector and DC current vector respectively. For DC grid, the active power injection $P_{DC,i}$ in node ***i*** in steady-state can be calculated by using (12).

$$P_{DC,i} = pU_{DC,i} I_{DC,i} \quad \forall i \leq k \tag{11}$$

$$P_{DC,i} = pU_{DC,i} \sum_{\substack{j=1 \\ j \neq i}}^{n} G_{DC,ij} \left(U_{DC,i} - U_{DC,j} \right) \tag{12}$$

Where ***p*** defines the topology of the DC grid, $p = 1$ is used for mono-polar topology and $p = 2$ for bipolar topology.

2) Converter and Line Outages Model

In DC network, the calculation for the converter outage can be done by modifying the DC current injection vector I_{DC} as in (13). Same approach can be used for DC buses, which are without a connection to AC network. Here ***l*** represents the number of converter outages

$$I_{DC} = \left[\underbrace{I_{DC1}, I_{DC2}, I_{DC3} \ldots\ldots I_{DCn-l}}_{ActiveConverter}, \underbrace{0 \ldots 0}_{ConverterOutage} \right]^T \tag{13}$$

For DC line outage, the derivation can be done by altering the DC bus conductance matrix G_{DC} accordingly.

III. AC/DC Load flow Implementation

The load flow algorithm for AC/DC distribution system is shown in Fig. 2. This algorithm adopts the iterative approach to analyze the integration of DC network into AC load flow algorithm. In this algorithm, initially DC slack bus power is estimated and then the AC load flow solution is derived. Then by using the calculated values, the VSC converter power and losses are calculated before running the DC network load flow algorithm. If system convergence is determined, the load flow algorithm will display the result otherwise it will repeat the process by updating new estimated value of DC slack bus power.

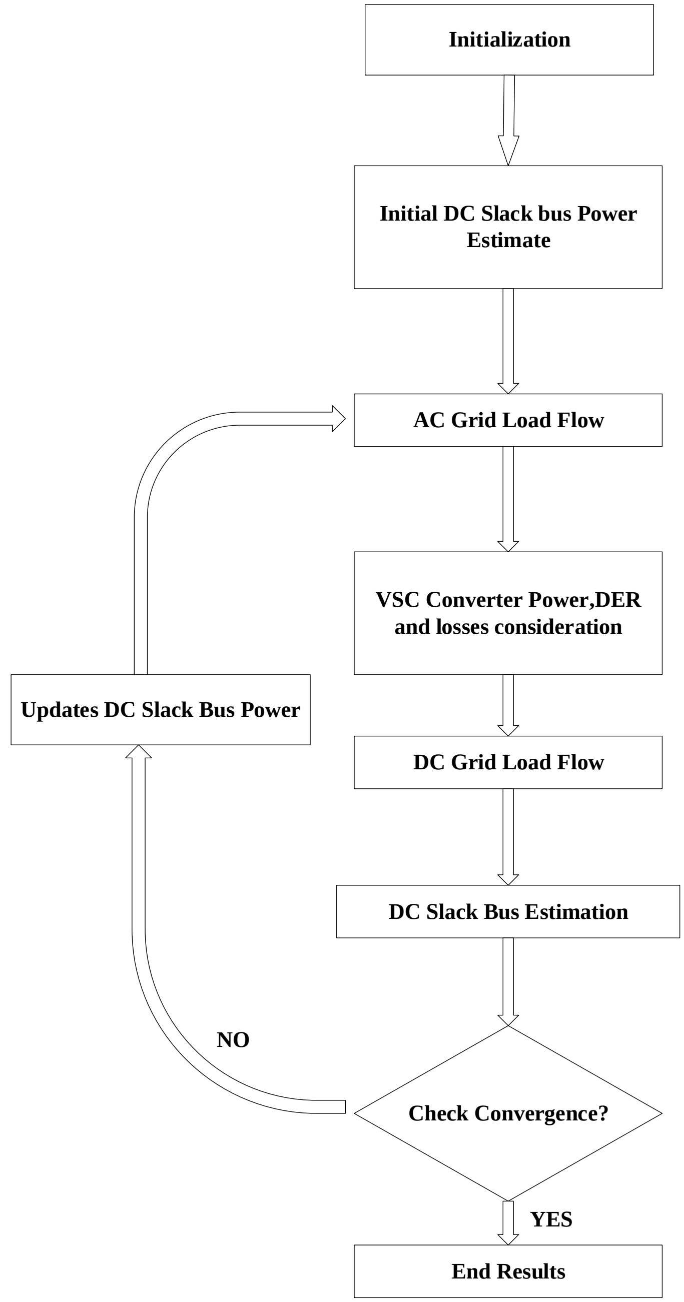

Fig. 2. AC/DC load flow algorithm [11]

A. Initial DC Slack bus setting

The active power injection for DC slack converter is unknown. At the first step of the algorithm, the initial value for DC slack converter power injection is estimated by considering the converter station and DC network to be lossless. Considering total ***n*** converters, where ***n***th converter is the slack converter and the rest of ***n* – 1** are considered as non-slack converters, then according to the law of conservation of power, the sum of power at converter station buses is zero.

$$0 = P_{AC,n}^{(0)} - \sum_{j=1}^{n-1} P_{AC,j} \tag{14}$$

Here superscript '0' represents the zero iteration.

B. AC Grid Load Flow

The active and reactive power load flow equations for AC network can be represented by (15)-(16)

$$P_i(U,\delta)=U_i\sum_{j=1}^{m}U_j\left[G_{ij}\cos(\delta_i-\delta_j)+B_{ij}\sin(\delta_i-\delta_j)\right] \quad (15)$$

$$Q_i(U,\delta)=U_i\sum_{j=1}^{m}U_j\left[G_{ij}\sin(\delta_i-\delta_j)-B_{ij}\cos(\delta_i-\delta_j)\right] \quad (16)$$

Here ***m*** represents the total number of AC network buses. The traditional Newton-Raphson (NR) load flow algorithm is used to determine voltages and phase angles for all AC buses using (17)

$$\begin{bmatrix}\Delta\delta^{(k)}\\ \dfrac{\Delta U^{(k)}}{U}\end{bmatrix}=-\left[J^{(k)}\right]^{-1}\begin{bmatrix}\Delta P^{(k)}\\ \Delta Q^{(k)}\end{bmatrix} \quad (17)$$

Here superscript ***k*** represents the AC/DC load flow iteration cycle.

C. Converter & DER power and losses

In order to extend the load flow algorithm to accommodate the VSC converter station and DER into the AC network, the converter power injections $P_{AC,i}$ and $Q_{AC,i}$ are included into power mismatch vectors as negative loads and are represented in (18)-(19). Similarly, for DER, the mismatch equations can be modeled as:

$$\Delta P_i^{(k)}=P_i^{Gen}-P_i^{Load}-P_i(U,\delta)+P_{AC,i} \quad (18)$$

$$\Delta Q_i^{(k)}=Q_i^{Gen}-Q_i^{Load}-Q_i(U,\delta)+Q_{AC,i} \quad (19)$$

P_i^{Gen} & Q_i^{Gen}: Active and Reactive Power generation from DER

P_i^{Load} & Q_i^{Load}: Load connected at buses

$P_{AC,i}$ & $Q_{AC,i}$: Active and Reactive Power injection by converters

$P_i(U,\delta)$ & $Q_i(U,\delta)$: Active & Reactive Power due to AC load flow

After AC load flow, the AC network voltage $U_{AC,i}$, active power $P_{AC,i}$ and reactive power $Q_{AC,i}$ injections and losses P_{loss} are calculated to obtain power injection to DC grid.

$$P_{DC,i}=-P_{c.i}-P_{loss,i} \qquad \forall i<n \quad (20)$$

D. DC Grid Load Flow

After AC load flow, the DC power injections P_{DC} are calculated using (12). By using the DC power injection vector, calculate the power mismatch vector ΔP_{DC} by NR method

$$\left(U_{DC}\frac{\partial P_{DC}}{\partial U_{DC}}\right)^{(j)}\cdot\frac{\Delta U_{DC}{}^{(j)}}{U_{DC}}=\Delta P_{DC}^{(j)} \quad (21)$$

For P_{AC}-control converter mode, the $\Delta P_{DC}^{(j)}$ is taken as $P_{DC,i}^{(k)}-P_{DC,i}(U_{DC}^{(j)})$ while in the case of converter outage the value is $-P_{DC,i}(U_{DC}^{(j)})$.

Here superscripts *j* referred to inner DC slack Bus mismatch iterations.

E. DC Slack Bus calculation

After DC load flow, the active power injection into the AC network by the DC slack bus is calculated by its DC power $P_{DC,n}$ and converter losses $P_{loss,n}$ as shown in (22)

$$P_{c,n}{}^{(k)}=-P_{DC,n}-P_{loss,n}{}^{(k)} \qquad \forall i\le n \quad (22)$$

The power mismatches $\Delta P_C^{(j)}$ and $\Delta Q_{AC}^{(j)}$ are then derived by first calculating $U_C^{(k)}$ and $\delta_C^{(k)}$ using Newton-Raphson iteration.

$$\begin{bmatrix}\Delta\delta_c^{(j)}\\ \dfrac{\Delta U_c^{(j)}}{\Delta U_c}\end{bmatrix}=-\left[J^{(j)}\right]^{-1}\begin{bmatrix}\Delta P_c^{(j)}\\ \Delta Q_{AC}^{(j)}\end{bmatrix} \quad (23)$$

$$\Delta P_c^{(j)}=P_c^{(k)}-P_c\left(U_{AC},U_c^{(j)}\right) \quad (24)$$

$$\Delta Q_{AC}^{(j)}=Q_{AC}-Q_{AC}\left(U_{AC},U_c^{(j)}\right) \quad (25)$$

F. Convergence Criterion

The DC slack bus $P_{c,n}$ convergence is fixed by the difference of DC slack bus value to be less then tolerance value 'ε' in two consecutive iterations as shown in (26).

$$\left|P_{c,n}{}^{(k)}-P_{c,n}{}^{(k-1)}\right|<\varepsilon \quad (26)$$

Thereafter the active power injection $P_{AC,n}$ and reactive power injection $Q_{AC,n}$ to the AC network is calculated using (1) and (2).

IV. Simulation Model And Results

In this paper MATPOWER [9] an open source MATLAB toolbox is used for the load flow analysis. Along with this another open source load flow program MATACDC [15], specially designed to address steady-state interactions between AC and DC networks based on VSC HVDC technology is used for the proposed analysis. MATACDC can be easily integrated with MATPOWER while keeping the source code unaltered.

A. Modeled Test Case

Simulations were carried out on a modified IEEE 14 bus AC/DC distribution network. Modified test network consist of two multi-terminal DC networks integrated into AC network through VSC Converters as shown in Fig. 3.

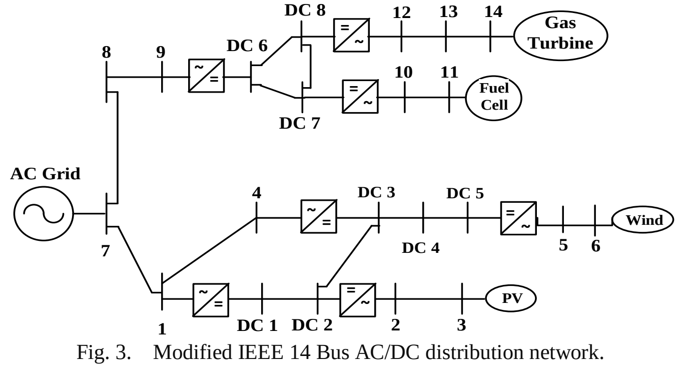

Fig. 3. Modified IEEE 14 Bus AC/DC distribution network.

The converters at DC bus 2 and 8 are chosen as DC slack converters, they adopts their reactive power injections to keep its DC bus voltages $U_{DC,2}$ and $U_{DC,8}$ constant. Bipolar topology (p = 2) of DC grid is under consideration for this analysis. The internal parameter details for VSC converter are given in Table I.

Different DER connected at different buses in the Modified IEEE 14 bus AC/DC distribution network are also considered in this analysis. The quantitative details of this DER are given in Table II.

TABLE II
SUMMARY OF DISTRIBUTION GENERATIONS (DG)

Source	PV	Wind	Fuel Cells	Gas Turbine Generation
Bus #	3	6	11	14
Capacity (MW)	0.04	0.02	0.03	0.02

B. AC/DC Load Flow Results

A tolerance of 1e-8p.u is used for the AC and DC network load flow. The load flow results in term of AC bus voltage for AC network without MTDC and AC/DC network integrated through MTDC are compared in Table III. Both load flow converges in 4 iterations with flat start.

TABLE III
AC BUS VOLTAGES WITH AND WITHOUT VSC MTDC SYSTEM

AC Bus #	Without MTDC U (p.u)	δ (rad)	With MTDC U (p.u)	δ (rad)
1	1.061	-0.020	1.061	0.009
2	1.000	-0.020	1.002	0.008
3	1.000	0.000	1.000	0.000
4	1.061	-0.030	1.062	0.024
5	1.000	-0.049	0.992	-0.755
6	1.000	0.000	1.000	0.000
7	1.060	0.000	1.060	0.000
8	1.073	-0.105	1.078	0.961
9	1.073	-0.105	1.078	0.977
10	1.000	-0.005	1.002	0.051
11	1.000	0.000	1.000	0.000
12	1.002	-0.089	0.983	-1.355
13	1.002	-0.089	0.997	-0.419
14	1.000	0.000	1.000	0.000

C. Converter Outage

This section discusses the effect of a converter outage on the load flows in AC/DC networks. In simulation results, the converter outage is considered at VSC converter that links AC bus 1 with DC bus 1. Table IV shows the effect on the voltages of DC buses due to converter outage. Table V discusses the effects on converter bus voltages due to VSC converter outage. Results show that converter the outage can affect the DC bus voltages and converter bus injection into the AC network.

D. DC Line Outage

The effect of DC line outage is analyzed by considering outage at DC line between DC bus 7 and 8. The DC line outage can occur by any kind of fault, especially due to line-to-line or line-to-neutral faults. The DC line outage can affects the voltages at DC buses as shown in Table IV. Table V shows the effect of DC line outage on converter buses.

Due to converter outage and DC line outage; there is a significant change in the power flow among the DC buses. Table VI shows the effect of changes in power flow among DC lines due to VSC Converter and DC line outages. With converter outage at DC bus 1 in MTDC network containing DC buses 1 to 5, the power flow from DC bus 1 become zero and there is a drastic change in magnitude of power flow from DC bus 2 to 5. No changes in power flow occur in second MTDC network from DC bus 6 to 8 due to converter outage at DC bus 1. Similarly, for DC line outage at DC line 7 and 8, the power flow magnitude also changes for DC bus 6 to 8 and no change in power flow magnitude occur from DC bus 1 to 5. This shows that both of the MTDC networks can be considered as independent from each other effects.

The power flow direction is taken as positive when power is flowing from DC network to AC network bus and vice versa.

TABLE IV
DC BUS VOLTAGES DUE TO CONVERTER & DC LINE OUTAGES

DC Bus #	With MTDC U (p.u)	Converter Outage U (p.u)	DC Line Outage U (p.u)
1	0.987	0.991	0.987
2	0.987	0.991	0.988
3	0.988	0.991	0.988
4	0.996	0.997	0.986
5	1.000	1.000	1.000
6	1.000	1.000	0.999
7	0.999	0.999	0.998
8	1.000	1.000	1.000

TABLE V
CONVERTER VOLTAGES

DC Bus #	With MTDC U (p.u)	δ(rad)	By Converter Outage U (p.u)	δ(rad)	By DC Line Outage U (p.u)	δ(rad)
1	1.047	0.505	0.000	0.000	1.047	0.505
2	0.998	0.950	0.998	0.950	0.998	0.950
3	1.048	0.520	1.047	0.506	1.048	0.520
4	0.997	0.945	0.997	0.945	0.997	0.945
5	0.978	-4.792	0.979	-3.876	0.978	-4.791
6	1.065	1.662	1.065	1.662	1.065	1.662
7	0.999	0.992	0.999	0.992	0.999	0.992
8	0.968	-3.735	0.968	-3.735	0.968	-3.737

TABLE VI
DC LOAD FLOW DUE TO CONVERTER & DC LINE OUTAGES

DC Bus		Pre Outage		Converter Outage		DC Line Outage	
From	To	From bus P(MW)	To bus P(MW)	From bus P(MW)	To bus P(MW)	From bus P(MW)	To bus P(MW)
1	2	-4.62	4.62	0.00	-0.00	-4.62	4.62
2	3	-11.74	11.75	-7.12	7.12	-11.74	11.75
3	4	-16.37	16.50	-11.74	11.80	-16.37	16.50
4	5	-23.61	23.70	-18.92	18.98	-23.61	23.70
6	7	1.57	-1.57	1.57	-1.57	7.12	-7.12
6	8	-7.68	7.69	-7.68	7.69	-13.24	13.25
7	8	-5.55	5.55	-5.55	5.55	0.00	0.00

V. CONCLUSIONS

In this paper, AC/DC load flow calculation was effectively analyzed for AC network integrated with VSC MTDC system. The proposed method was implemented and tested on a modified IEEE 14 bus distribution network interconnected with DER with no limits on the number of converters or on DC network topology. The objectives of this paper are the implementation of outages in VSC converter and DC line and analyze its effects on load flow characteristics on post-disturbance steady-state network. MATPOWER, toolbox was used for this analysis. The simulation results show the effects of Converter and DC line outage on the load flow in the system. With the development in different control strategies for power and voltage control in the network, droop control mechanism can also be implemented for the load flow analysis in the proposed model in future. Also a large network with higher number of nodes and converter connected can be consider to more clearly understand the effects of multiple converter and DC line outages on networks.

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