Analyzing the effects of converter and DC line outages due to Distributed Voltage Control in AC-MTDC Distribution Network

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Abstract- Technological advancements in power electronics devices in recent years and the increase in the integration of distributed energy resources (DER) due to green energy awareness has transformed the conventional power network into a sophisticated and smart network. With the large-scale integration of sensitive DC load along with AC, and availability of DER with AC and DC type outputs results in an inevitable shift to develop an efficient and reliable layout for a distribution network known as AC-MTDC distribution network. In this paper, an AC-MTDC distribution network is realized to perform the load flow analysis, employing voltage source converter (VSC). A distributed DC voltage control technique is also implemented on VSC based AC-MTDC distribution network, and its effects are analyzed considering the converter and DC line outages for various network scenarious. A modified IEEE 33-bus AC-MTDC distribution network with VSC is considered for this study, and results are analyzed according to power sharing requirement and operational efficiency using MATPOWER, an open source power flow package.

Keywords Distributed voltage control, AC Multi-Terminal DC (AC-MTDC) Distribution Network; Load Flow Analysis; Voltage Source Converter.

1. Introduction

Modern power delivery networks have gone through a revolutionary technological advancement in recent decade due to the integration of renewable energy resources and increase in usage of the modern and technical advance power electronic devices. Due to substantial rise in number of different types of AC and DC loads and an improvement in an advance control mechanism with the help of power electronics devices makes the modern power networks more efficient, reliable and smarter. With an increase in interest for development of green and efficient networks, one of the best opportunities is the AC-MTDC based distributed network. Despite having many barriers such as cost and efficiency of converter stations and other DC components such as DC circuit breaker, AC-MTDC network configuration can offer many advantages, including simple expansion of the system, enhanced redundancy and reliability of the network, flexibility in the supervisory control for power dispatch, accommodating the intermittent nature of renewable energy resources, and efficient utilization of cables, bi-directional power flow and multi stage conversion of converters [1]-[3]. Presently, there are multiple plans which have been under consideration for the commercial implementation of DC network all over the world [4]-[7].

With the development in power converter technology, a new concept of hybrid AC-MTDC distribution networks have been under investigation and it could demonstrate the advantages of both AC and DC system into a single network.

AC-MTDC based distribution network can offer technical and economic advantages over traditional AC networks and can be easily interconnected in the existing AC infrastructure at various points [8]-[10]. For practical implementation, the promising technology for the interconnection of AC and DC networks through multiple converters in the same network is the Voltage Source Converter (VSC). This technology is already being implemented in a few of the projects around the world [11]-[14].

One of the outstanding research issues in the AC-MTDC network is the DC voltage control that indicates the system overall safety and stability of the network. According to the literature, the DC voltage control techniques can be classified as the centralized DC slack bus control and the distributed DC voltage control [15]. In most of the centralized DC slack bus control method for the VSC based AC-MTDC network configuration, the network consists of one bus terminal to regulate the DC voltage (DC slack bus) for the network and its power act as to compensate for the power and the losses imbalance of the overall DC network, while the remaining DC buses regulated the active power injection from all other converters into the AC network. However, this method has many disadvantages and can require specific conditions for proper implementation such as the DC slack terminal must be over-rated and must be connected to a strong AC network to ensure that the DC bus voltage remains in its reference value, else a lot of stress on the slack bus in case of transient may result in the loss of this converter bus which leads to instability of the whole DC network. The other solution for the DC voltage control technique is the distributed DC voltage control method to enhance the reliability of DC network by employing the active power regulation at multiple buses such that multiple converters simultaneously helps for DC voltage stability in the network as illustrated by [16]-[18]. In this approach, the DC voltage has to be regulated on several DC converter buses at the same time and the power setting of the slack converter bus in linked with the variation in the associated DC converter bus voltage. In this study, a distributed DC voltage control technique is implemented considering the stable operation of VSC based AC-MTDC distribution network and results are compared with the conventional load flow analysis technique. Few cases, considereing converter and DC line outages are also analyzed using these techniques.

The rest of the paper is organized as follows. Section 2 describes the VSC station modeling and discusses about the operation and control of the VSC based AC-MTDC distribution network. Section 3 discusses the load flow algorithm for the analysis of VSC based AC-MTDC distribution network. In section 4, modified test network and simulation results are analyzed for different network configurations along with the occurrence of any abnormal scenario within the network due to the converter or DC line outages. Finally, concluding remarks are presented in section 5.

2. VSC Station Modelling and Distributed Voltage Control Mode

This section discusses the general modeling of VSC for the AC-MTDC based network configuration. In general, the VSC station plays the essential building block in the integration of AC and DC network configuration, and the direction of the flow of power through VSC depends upon its operation of controls as rectifier or inverter. When the flow of active power is from the AC network into the DC network, the converter is operating as a rectifier. On the other hand, if the flow of power is from the DC network to the AC network through the VSC, the VSC is considered to be operating as an inverter.

2.1. VSC-Station Modelling

Fig. 1 illustrates the general approach for the representation of VSC-station in this paper. The VSC-station model is represented as a controllable voltage source $U_c = U_c\angle\delta_c$ along with complex impedance [19]. The complex impedance can be further distinguished among interfacing transformer impedance, low pass shunt filter and phase reactor represented as $Z_{tf} = 1/Y_{tf} = R_{tf} + jX_{tf}$, $Z_f = 1/Y_f = jX_f$ and $Z_c = 1/Y_c = R_c + jX_c$ respectively. $\mathbf{U_{PCC}} = U_{PCC}\angle\delta_{PCC}$ and P_{PCC}, Q_{PCC} represents the voltage output at the point of common coupling (PCC), active and reactive power injections at the point of common coupling to the AC network respectively. Similarly, the expression for the voltage output at interface transformer voltage, converter bus and at filter are represented by $\mathbf{U_{tf}} = U_{tf}\angle\delta_{tf}$, $\mathbf{U_c} = U_c\angle\delta_c$ and $\mathbf{U_f} = U_f\angle\delta_f$ respectively. The power flow to the AC network from the converter side is expressed by P_c and Q_c, while the DC bus output voltage and DC power are shown by $\mathbf{U_{DC}}$ and P_{DC}. Where '*i*' represents the DC converter bus number.

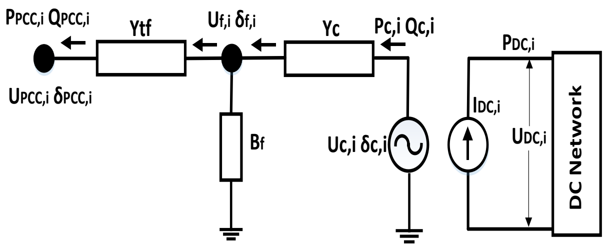

Fig. 1. VSC-Station Equivalent circuit model

The active and reactive power of the VSC-station model in steady state can be calculated with the help of following equations [18].

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

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

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

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

Where

G_{tf} represents the conductance of interface transformer

G_c represents the conductance of the converter

B_{tf} represents the susceptance of interface transformer

B_c represents the susceptance of the converter

2.2. Distributed Voltage Control at DC converter bus in AC-MTDC distribution network

Linking variation in DC bus power with DC bus voltage (Voltage-Power) is the widely proposed voltage control approach for the distributed voltage control method in the literature, and can be easily adopted in VSC based AC-MTDC distribution networks [21-24]. For the employment of distributed voltage control at DC converter bus in a DC network, the converter rectifying power would be controlled according to (5)

$$P_{DC} = P_{DC,0} - \frac{1}{K_{DC}}(U_{DC} - U_{DC,0}) \quad (5)$$

Where PDC,0 and UDC,0 are the distributed voltage control set-points for voltage and power respectively, while KDC is equal to ΔUDC/ΔPDC which represent the distributed voltage control variable as shown in Fig. 2.

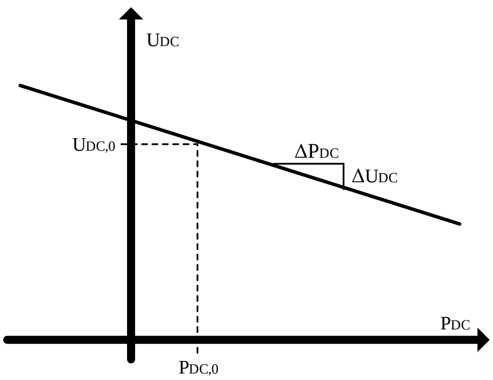

Fig. 2. Distributed DC voltage control characteristic for the DC converter bus

The principle of operation of the distributed voltage control is that when there is a variation in the value of the active power injected into the AC network will result in an associated change in the DC converter bus voltage. Such in a case that when there is a large withdrawal of power in the DC network will result in an increase in the active power injection by the DC converter slack bus into the DC network causing DC bus voltage to drop and a new equilibrium point is adopted at a lower DC voltage.

2.3. VSC-Station operations control modes for AC-MTDC distribution network

The VSC technology because of its advantage to independently control the active and reactive power regarding the AC network, the VSC operation can be represented by different operation control modes. The ability of the converter to control its active power injection independently can be modeled in the following ways in the load flow algorithm [19].

1) Constant P_{PCC}-control: In this mode, the converter controls its constant active power injection at the point of common coupling P_{PCC} into the AC network.

2) Constant U_{DC}-control: In this mode, the converter controls its constant DC voltage U_{DC} at its terminal irrespective of its active power injection at the point of common coupling P_{PCC}.

3) P_{PCC}-U_{DC} Distributed voltage control: In the mode, the active power injected into the DC network P_{DC} depends upon the DC bus voltage U_{DC} according to distributed voltage control characteristics of the DC bus.

For the reactive power control, the control modes can be represented as

1) Constant Q_{PCC}-control: In this mode, the converter controls its constant reactive power injection at the point of common coupling Q_{PCC} into the AC network.

2) Constant U_{PCC}-control: In this mode, the converter controls its constant bus voltage at the point of common coupling U_{PCC} by adjusting the reactive power injection Q_{PCC} at the PCC.

When the VSC-station is used as a rectifier, the control mode is set as constant P_{PCC}–constant Q_{PCC} control to independently control the active and reactive powers at the point of common coupling. When used as an inverter, the control mode is set to constant U_{DC} -constant Q_{PCC} control of its operation. The distributed voltage control is used to share the active power among the distributed voltage control buses in the DC network.

2.4. VSC Loss calculation

For the converter losses calculation, a generalized polynomial expression is used in which the converter losses are expressed in term of values and direction of the phase current I_c of the converter [17]. The phase current Ic will be taken as positive value when the converter is injecting it into the AC network, and taken as negative value when in the opposite direction. The mathematical expression of the converter losses can be represented as (6)

$$P_{C.loss} = R_1 + R_2.\left|I_c\right| + R_{inv}\ .(I_c)^2 + R_{rec}\ .(I_c)^2 \quad (6)$$

Table 1. VSC Converter Data

Converter Loss Coefficient (p.u)	**Converter Data (p.u)**

R_1	0.011030	R_t	0.0015
R_2	0.003463	X_t	0.1121
R_{rec}	0.0044	B_f	0.045
R_{inv}	0.00667	R_c	0.0001
		X_c	0.1642

Where R_1, R_2, R_{inv} and R_{rec} are the per unit converter loss coefficients. Depending upon the direction of the active power transfer, an extra condition is added that only one of the quadratic term $R_{inv}.(I_c)^2$ or $R_{rec}.(I_c)^2$ will be active at a time depending upon the operation of the converter as an inverter or as a rectifier respectively. The per unit converter loss coefficient and converter data used in this study are given in following Table 1.

3. Load Flow Algorithm for VSC Based AC-MTDC Distribution Network

The load flow algorithm for AC-MTDC distribution network is shown in Fig. 3. The algorithm adopts the sequential approach to analyze the AC-MTDC network, described in steps as follows.

Step 1: Input data for the AC-MTDC network and converters and convert it to the same per unit base. Determine the network layout and differentiate it into AC and DC networks and sub-networks. At the initial stage, the DC networks and converters are assumed to be lossless, so all converter data and DC network data are considered to be constant.

Step 2: Determine the characteristic of the network/sub-network. If the network is AC, determine the converter's active power injection into the AC network from the DC networks. The active power injections for converter under DC voltage control (slack control and/or distributed voltage control) are not known, so the AC active power injections are put equals to the negative of the DC reference power assuming the reference DC voltage value does not change. The active power delivered by the DC (slack control and/or distributed voltage control) is given by (7)

$$P_{PCC} = -\sum_{i=2}^{m} P_{PCC,j} - \sum_{j=m+1}^{n} P_{PCC,j} \qquad (7)$$

Where

m = Total number of distributed voltage control buses

n = Total number of converters connected to AC buses at the point of common coupling

Step 3: Analyze the AC network by standard Newton load flow algorithm, calculate the active power injection $P_{c,i}$ at the converter side and converter losses $P_{C.loss,i}$.

Step 4: Determine the characteristic of the next network/sub-network. If the network is DC, calculate the active power injection $P_{DC,i}$ from the AC network using the power coupling equation as shown in (8).

$$P_{DC,i} = -P_{c.i} - P_{C.loss,i} \forall i < n \qquad (8)$$

Apply the load flow method to solve the DC network.

Step 5: Continue to determine the characteristic of the next network/sub-network. If the network is an AC sub-network return to Step 2, else if the network is a DC sub-network return to step 4. If all the sub-networks are analyzed and "AC network 1" is arrived, go to step 6.

Step 6: Determine the characteristic of the network, if it is the "AC network 1", calculate the active power injection of the converter P_c using (9). This P_c depends upon the DC power P_{DC} of the voltage controlled bus (Slack or Droop) along with converter losses.

$$P_{c,n}^{(k)} = -P_{DC,n} - P_{C.loss,n}^{(k)} \qquad (9)$$

Where "k" represent the iteration number.

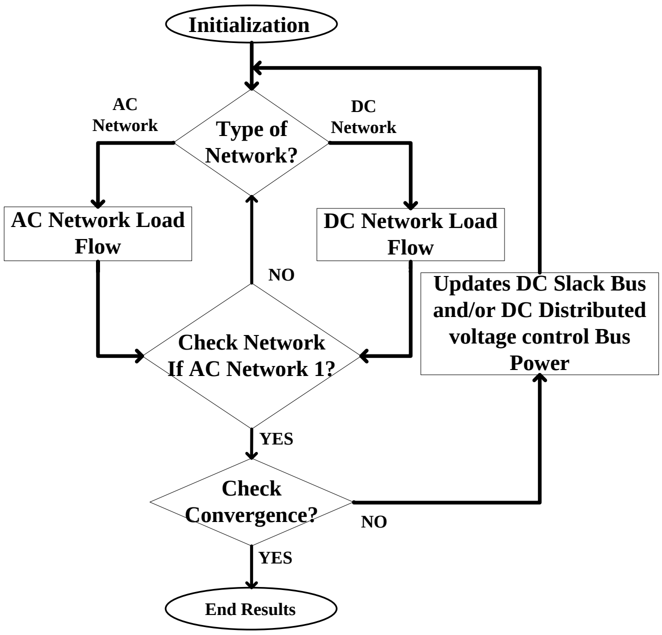

Fig. 3. Flow Chart for load flow analysis of VSC based AC-MTDC Distribution network

Step 7: The convergence criteria of the algorithm are set on the difference of combined power injections into the AC network from the slack converter power and the distributed voltage control buses. If the results converged, the calculation is complete, otherwise return to step 2 with the new DC system data acquired at current iteration.

4. Test System and Simulation Analysis

4.1. Generic AC-MTDC Distribution Network configuration with VSC

At the convention in AC distribution network, a single generation source is used for the supply of power to the interconnected loads as the network layout. With the integration of distributed energy resources into the network at distribution level and to adopt the VSC based AC-MTDC distribution network, the modified network will be transformed into several AC and DC sub-networks acting as integrated network through VSC as shown in Fig. 4.

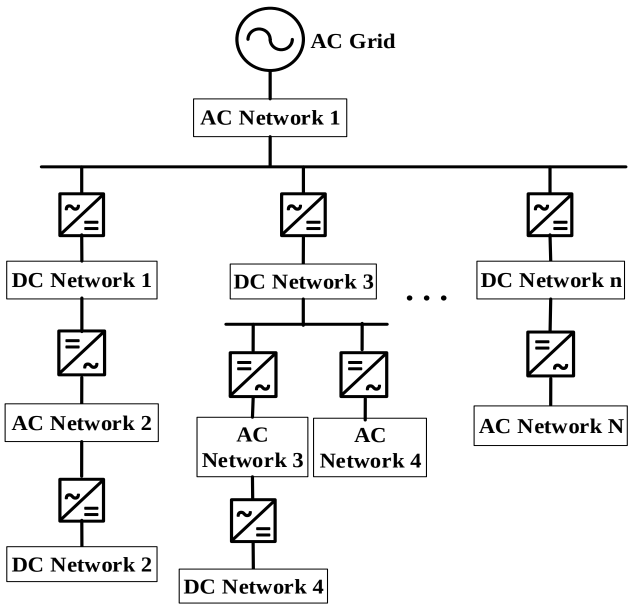

Fig. 4. Network layout for VSC based AC-MTDC distribution network

For the analysis of VSC based AC-MTDC distribution network, the first AC network shown as "AC network 1" is considered to be directly connected with the main transmission grid. Other AC networks are considered as sub-networks and they are interconnected with one or more DC networks through VSC. The power supplied to the "AC network 1" is considered from the main transmission grid while in the rest of the AC and DC sub-networks the power is supplied by the distributed energy resources (DER) through the bi-directional flow of power through VSC.

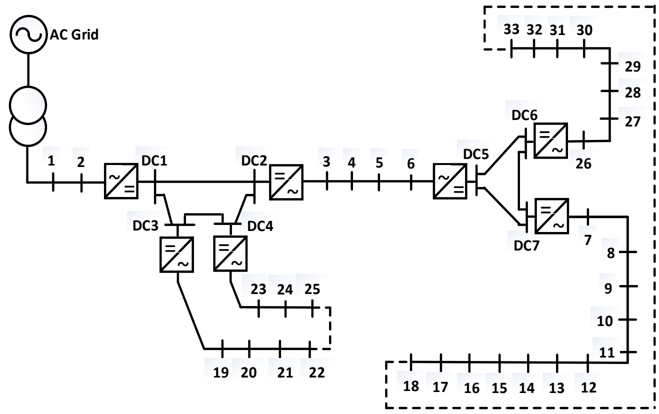

Fig. 5. Modified IEEE 33-bus AC-MTDC Distribution network

4.2. Description of proposed Test System

In this section, the IEEE 33-bus distribution network is modified into an AC-MTDC distribution network for the implementation and analysis of this algorithm. It is assumed that the DC networks are bi-polar and the loads are connected to both the positive and negative poles. The implementation and validation of the algorithm are analyzed using MATPOWER [25], an open source MATLAB toolbox for load flow study, which is designed to address steady-state analysis of AC-MTDC networks integrated with VSC system. As shown in Fig. 5, the single line diagram of the modified test system composed of two separate MTDC links consisting of seven VSCs mainly functioning as the interconnections between the main AC network with the AC and DC sub-networks. In this analysis, four DERs of different capacities are considered to be connected within the network at different bus locations as mentioned in Table 2.

Table 2. Summary of Distributed Energy Resources (DER)

Source	Bus #	Capacity (MW)
DER I	18	6
DER II	22	3
DER III	25	6
DER IV	33	3

Three different case studies were considered in the analysis, depending upon the radial or meshed configuration of the network while considering the slack bus control or distributed voltage control characteristics of the converter buses in the DC network. The cases can be listed as below:

Case 1: In this case, a radial network scenario is considered with DC buses 1 and 5 are under DC slack bus control while the rest of the DC buses are considered under the constant power control.

Case 2: In this case, a radial network scenario is considered with DC buses 1 and 5 are slack buses, while all DC buses are considered under the DC distributed voltage control.

Case 3: In the case, a meshed network scenario is considered with meshed buses shown as dotted lines in Fig. 5. The DC network configuration is kept same as in case 2 for DC slack and distributed control buses.

4.3. Simulation results

A tolerance of 10^-8 (p.u) is used for the convergence criteria with the flat start consideration. The load flow results for the AC buses and DC buses are presented in Table 3 and Table 4 respectively. From the load flow result for the AC network in Table 3 for the above mentioned cases, it can be seen that there is an improvement in the voltage profile for the meshed configuration networks with distribution voltage control characteristics. Table 4 shows that the voltage level in the different VSC stations lies within the acceptable voltage range between 0.9 and 1.1 p.u. As shown in Table 5, a decrease in the losses is observed for the radial configuration with distributed voltage control characteristics in case 2 as compared to losses in a radial configuration with slack bus control characteristics in case 1 was considered. An increase in losses was observed in the meshed configuration with distributed voltage control because of extra AC buses in meshed network.

Table 3. AC bus Voltages for different cases

Case 1: Radial+slack Case 2: Radial+Distributed Voltage Control Case 3: Meshed+Distributed Voltage Control

AC Bus	Case 1 U(p.u) δ(rad)	Case 2 U(p.u) δ(rad)	Case 3 U(p.u) δ(rad)
1	1.000 0.000	1.000 0.000	1.000 0.000
2	1.000 -0.008	1.008 0.218	1.005 0.116
3	1.000 0.000	1.000 0.000	1.000 0.000
4	0.999 -0.023	1.021 0.562	1.009 0.159
5	0.998 -0.046	1.042 1.124	1.018 0.321
6	0.997 -0.134	1.090 3.102	1.039 1.019
7	1.000 0.000	1.000 0.000	1.000 0.000
8	1.002 0.055	1.002 0.055	1.007 0.149
9	1.005 0.207	1.005 0.207	1.017 0.582
10	1.008 0.360	1.008 0.360	1.027 1.008
11	1.009 0.374	1.009 0.374	1.029 1.046
12	1.010 0.402	1.010 0.402	1.033 1.118
13	1.015 0.637	1.015 0.637	1.047 1.762
14	1.017 0.778	1.017 0.778	1.053 2.152
15	1.019 0.884	1.019 0.884	1.059 2.437
16	1.021 0.995	1.021 0.995	1.066 2.728
17	1.026 1.341	1.026 1.341	1.080 3.642
18	1.028 1.457	1.028 1.457	1.088 3.935
19	1.000 0.000	1.000 0.000	1.000 0.000
20	1.002 0.139	1.002 0.139	0.950 -2.560
21	1.003 0.188	1.003 0.188	0.936 -3.523
22	1.004 0.285	1.004 0.285	0.914 -5.477
23	1.000 0.000	1.000 0.000	0.836 -5.119
24	1.003 0.143	1.003 0.143	0.866 -2.991
25	1.006 0.288	1.006 0.288	0.898 -1.025
26	1.000 0.000	1.000 0.000	1.118 5.102
27	1.000 0.021	1.000 0.021	1.116 5.077
28	1.001 0.128	1.001 0.128	1.110 4.870
29	1.002 0.210	1.002 0.210	1.104 4.714
30	1.003 0.246	1.003 0.246	1.101 4.667
31	1.004 0.342	1.004 0.342	1.096 4.432
32	1.004 0.368	1.004 0.378	1.094 4.342
33	1.005 0.434	1.005 0.434	1.092 4.209

4.3. Converter and DC line outage assessment of VSC based AC-MTDCdistribution network

In this section, the effects of a converter outage and the DC line outage on the load flow of the VSC based AC-MTDC distribution network is analyzed. This algorithm helps in analyzing the effects of the distributed voltage control characteristics of the load flow by considering the converter outage and DC line outages at various locations in the network [26-27]. Four different cases were analyzed with two converter outage and two DC line outage at different locations within the network one by one and their results are summarized below.

Table 4. Converter Voltage results for DC networks

Case 1: Radial+slack Case 2: Radial+Distributed Voltage Control Case 3: Meshed+ Distributed Voltage Control

Converter #	K_{DC}	Case 1 Voltage Mag (p.u)	Case 2 Voltage Mag(p.u)	Case 3 Voltage Mag (p.u)
VSC_{DC1}	0.005	0.985	1.089	1.036
VSC_{DC2}	0.007	0.980	1.017	1.008
VSC_{DC3}	0.005	0.976	1.014	1.014
VSC_{DC4}	0.005	0.983	1.016	0.965
VSC_{DC5}	0.007	0.982	1.090	1.048

VSC_{DC6}	0.005	0.985	1.000	1.097
VSC_{DC7}	0.005	0.985	1.016	1.016

Table 5. Loss calculations for AC-MTDC Distribution network

Case 1: Radial+slack Case 2: Radial+Distributed Voltage Control Case 3: Meshed+ Distributed Voltage Control

	Case 1	Case 2	Case 3
Total AC network losses (p.u)	0.1235+j0.02	0.0738+j0.062	0.1313+j0.122
Total DC network losses (p.u)	0.0110	0.0135	0.0149
Total converter losses (p.u)	0.0801	0.1222	0.1008
Total losses (p.u)	0.2146+j0.02	0.2095+j0.062	0.237+j0.122

Case 3A: In this case, a converter outage is considered at VSC-4 connecting AC bus 23 to DC bus 4.

Case 3B: In this case, a converter outage is considered at VSC-6 connecting AC bus 26 to DC bus 6.

Case 3C: In this case, a DC line outage is considered at line connecting DC bus 1 and 2.

Case 3D: In this case, a DC line outage is considered at line connecting DC bus 5 and 7.

Table 6. Power flow And Converter Volatge results for DC networks due to converter outage

DC Bus	Case 3A		Case 3B	
From-To	From	To	From	To
1-2	4.02	-4.02	-15.94	15.97
1-3	-40.57	40.65	-68.98	69.20
2-4	-9.14	9.15	-29.13	29.24
3-4	9.16	-9.15	-19.66	19.72
5-7	-30.26	30.31	-34.05	34.11
5-6	-8.37	8.38	-15.69	15.71
6-7	19.56	-19.54	15.72	-15.71
Converter #	**Voltage Mag (p.u)**		**Voltage Mag (p.u)**	
VSC_{DC1}	1.012		1.036	
VSC_{DC2}	1.008		1.008	
VSC_{DC3}	1.014		1.014	
VSC_{DC4}	0.000		0.865	
VSC_{DC5}	1.048		1.060	
VSC_{DC6}	1.107		0.000	
VSC_{DC7}	1.016		1.016	

A change in power flow in both AC and DC network were observed due to the converter and DC line outages. The variations in the power flow results for DC and AC networks due to converter and DC line outage are shown in Table 6 and Table 7 respectively. The power flow direction is taken as negative when power is flowing from AC network to DC network bus and vice versa. These above mentioned outage has caused the voltage level to rise out of an acceptable voltage range (between 0.9 and 1.1 p.u.) which could cause a reversal of power flow across other converters as compared to steady-state operation of the meshed network. This may cause damage to AC and DC network along with the converters due to current flow limitation for the lines.

Table 7. Power flow And Converter Volatge results for DC networks due to DC Line outage

DC Bus	Case 3C		Case 3D	
From-To	From	To	From	To
1-2	0.00	0.00	-15.94	15.97
1-3	-84.07	84.40	-68.98	69.20
2-4	-13.16	13.18	-29.13	29.24
3-4	-35.01	35.31	-19.66	19.72
5-7	-30.26	30.31	0.00	0.00
5-6	-8.37	8.38	-37.78	37.86
6-7	19.56	-19.54	15.72	-15.71
Converter #	**Voltage Mag (p.u)**		**Voltage Mag (p.u)**	
VSC_{DC1}	1.035		1.036	
VSC_{DC2}	1.008		1.008	
VSC_{DC3}	1.014		1.014	
VSC_{DC4}	0.868		0.865	
VSC_{DC5}	1.048		1.047	
VSC_{DC6}	1.107		1.107	
VSC_{DC7}	1.016		1.016	

5. Conclusion

In this paper, a load flow model has been presented to analyze the effects of distributed voltage control on the VSC based AC-MTDC distribution networks. This load flow model can help in analyzing any generalized network layout or topology with no limitation in number of AC and DC buses in sub-networks. Different case studies were performed to analyze and compare the load flow results for the slack and distributed voltage control characteristics having radial and/or meshed network configuration. Distributed Voltage control causes a reduction in the network losses for radial networks while meshed network causes an increase in overall network losses due to the addition of AC buses. The effects of converter outage and DC line outages on the load flow of AC-MTDC distribution network were also considered with the help of this algorithm and the variations in the direction of the power flow between AC and DC networks were observed due to these outages.

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