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Reliability Evaluation of Multi Terminal HVDC transmission Systems

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Abstract: High Voltage Direct Current (HVDC) systems are used to transmit the electric power /energy to long distances compared to High Voltage Alternative Current(HVAC) systems. In HVDC systems AC/DC converters are used at each end of the link. If the HVDC system is designed with more than two terminals is called Multi Terminal Direct Current (MTDC) systems. Two types of converters such as thyristor operated converters (CSCs) and IGBT operated Converters (VSCs) are used in MTDC systems. Practically VSC-MTDC are more suitable than CSC-MTDC. This paper discusses the reliability analysis of three developing technologies of MTDC systems and also proposed VSC-MTDC is more reliable than CSC-MTDC.
Key Words: MTDC systems, CSC-HVDC,VSC-HVDC, reliability indices

1. Introduction:

Multi terminal HVDC transmission system consists converters at all terminals. Some of them work as inverter and others as rectifiers[6]. Depending upon the connection of converters multi terminal HVDC systems are series connected and parallel connected MTDC systems[9]. Parallel connected MTDC systems are more reliable than series connected MTDC systems because of its increase in power requirement, less losses etc [3].

2. Basic Methodology:

Several methods are used to analyze the reliability of transmission systems, such as even tree, cut set method, Markov modeling etc. In this paper Markov modeling is used to evaluate the reliability of components of HVDC system[7]. A Markov model can be useful to the systems whose random behavior varies either discretely or continuously with time[5].

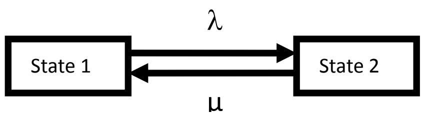

Fig 1 state space diagram of two state model

Fig 1 consists two states one is up state (state 1) and another is down state (state 2). And two transitions associated with each component, the first λ representing the failure rate and the second μ represents the repair time.

3. Developing Technologies in VSC-MTDC

Now a days Voltage Source Converter operated HVDC transmission systems are used in MTDC systems because of its lower investment cost, increased availability etc[2]. According to type of converter used at the terminal of MTDC are classified into
i: Combined CSC and VSC
ii: Multi Terminal VSC
iii: CSC and VSC Multi Terminal with CSC converter used only at the bulk power source

i Combination of CSC and VSC :
Combination of CSC and VSC, multi terminal DC system is shown in the Fig 2.

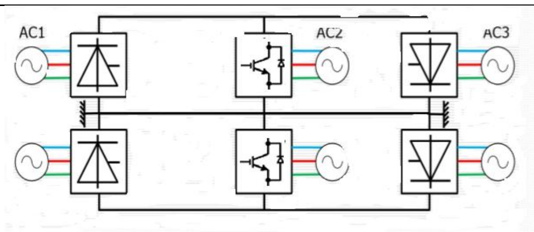

Fig 2 Combination of CSC and VSC Multi Terminal HVDC System

In Fig 2 sending end consists parallel connected current source and voltage converters. Where the receiving end is with current source converter.

ii Multi Terminal VSC: Fig 3 shows the multi terminal VSC. .

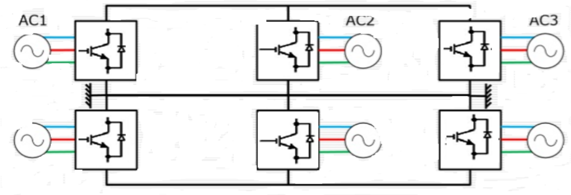

Fig 3 Multi Terminal VSC-HVDC System

In Fig 3 two voltage converters are connected in parallel at the sending end, where the receiving end has voltage source converter.

iii CSC and VSC multi terminal with CSC converter used only at the bulk power source

Combination of CSC and VSC with current source converter as power source at sending end is as shown in the Fig 4.

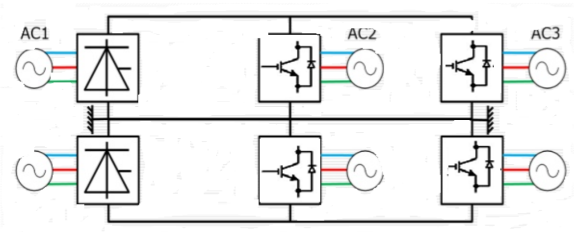

Fig 4 CSC and VSC multi terminal with CSC converter used as power source

3 Base Case: System shown in the Fig 5 is used as a base case system. Two converters at the sending end provides 600MW each therefore the generating capacity of 500kV transmission system at the sending end is to be 1200MW. The base case of 1200MVA(1p.u) is considered. The transmission line capacity is equal to 1p.u. and the transmitted power on the line can vary between 0p.u to 1p.u. The length of the transmission line is 500km. Assumed the load at the receiving end is 960MW(0.8p.u)[11].

4. Reliability evaluation of MTDC systems:

The reliability of MTDC systems, can therefore be achieved by creating appropriate reliability models of the converters at the end of the terminals of HVDC[4,12]. Fig 5 and Fig 6 shows the configuration of current source and voltage source converters.

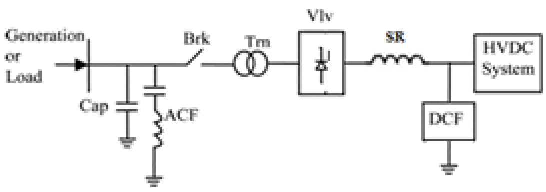

Fig 5 Configuration of Current Source Converter

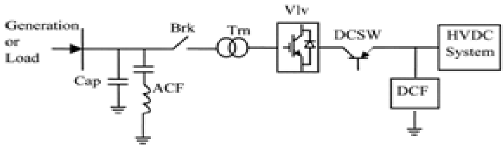

Fig 6 Configuration of Voltage Source Converter

In Fig 5 thyristors are operated in the converter. Where in Fig 6 IGBTs are operated in the converter. Comprehensive reliability model of multi terminal VSC with CSC converter used as a power source is as shown in Fig 7. In Fig 7 both converter models CSC and VSC are same except subsystem 2 and 8 [13].

4.1Analysis and procedure: Using state diagram of Fig 1, reliability values of each component of HVDC transmission system, for forced outage data of APPENDEX-A are calculated and tabulated as shown in Table 1.

Table 1 Reliability values of each component of HVDC

Component	Reliability
ACF	0.9996301
Cap	0.9999983
DCF	0.9994523
SR	0.9982901
Vlv	0.9968530
Brk	0.9999143
DCTL/km	0.9999998
Trn	0.99935

For Fig 7 Capacities per unit states of subsystem 1 to 8 are tabulated as shown in Table 2. In Fig 7 all the components in the subsystems are connected in series and parallel structure [8].The subsystem 8 model is simplified based on the capacity outage per unit values which are considered from APPENDIX-C probability, equivalent λ_-(occ/yr) and λ_+(occ/yr) transition rates are evaluated and tabulated in Table 2 as subsystem 8.

Table 2 Reliability models associated with subsystems 1 to 8

Subsystems	Capacity[p.u]	probability	λ_+[occ/yr]	λ_- [occ/y/r]
subsystem 1	1	0.99925767	0	1.084
	0.9	2.74E-6	1460	1.082
	0.65	7.3945E-4	140	0.544
	0.62	1.88E-12	2920	1.08
	0.6	2.03E-8	2920/	0.542
	0.3	1.39E-15	438/0	0.54
	0	1.37E-7	29/20	0
2 or 7	1	0.99264394	0	1.17
	0.5	7.34249E-3	313.5	0.585
	0	1.35779E-5	627	0
3 or 6	1	0.99890441	0	0.8
	0.75	0.00109529	730	0.4
	0	3xE-7	1460	0
4 or 5	1	0.99999144	0	0.015
	0.5	8.56E-6	35.04	0.0075
	0	1.83E-11	70.08	0
sub system 8	1	0.999315364	0	1
	0.9	6.844625E-4	1460	0.75
	0.6	1.75803E-7	2920	0.5
	0.3	2xE-11	4380	0.25
	0	8.5911E-16	5840	0

Taking one by one sub systems 1 to 8 the following steps are used to simplify the Table 2 to find the final reliability model of base case system

4.1.1 Algorithm to find the reliability model of base case system:

Step 1: Take the n,c,x[10],y[10],λ_+(occ/yr),λ_-(occ/yr) and z[10], where n and m are the number of states in x[10] and y[10], c be the capacity per unit of the state, λ_+ (occ/yr) and λ_-(occ/yr) represents the upward and down ward transition rates of corresponding capacity c.

Step 2: Read the arrays x[i],y[j],λ_{+i} (occ/yr) ,λ_{-i} (occ/yr), λ_{+j} (occ/yr) ,λ_{-j} (occ/yr),n,m and c

Step 3: for i=0 to n, j=0 to m then repeat

(a) if c = =1 then

z[i] = x[i] * y[j]

λ_{+i} = 0

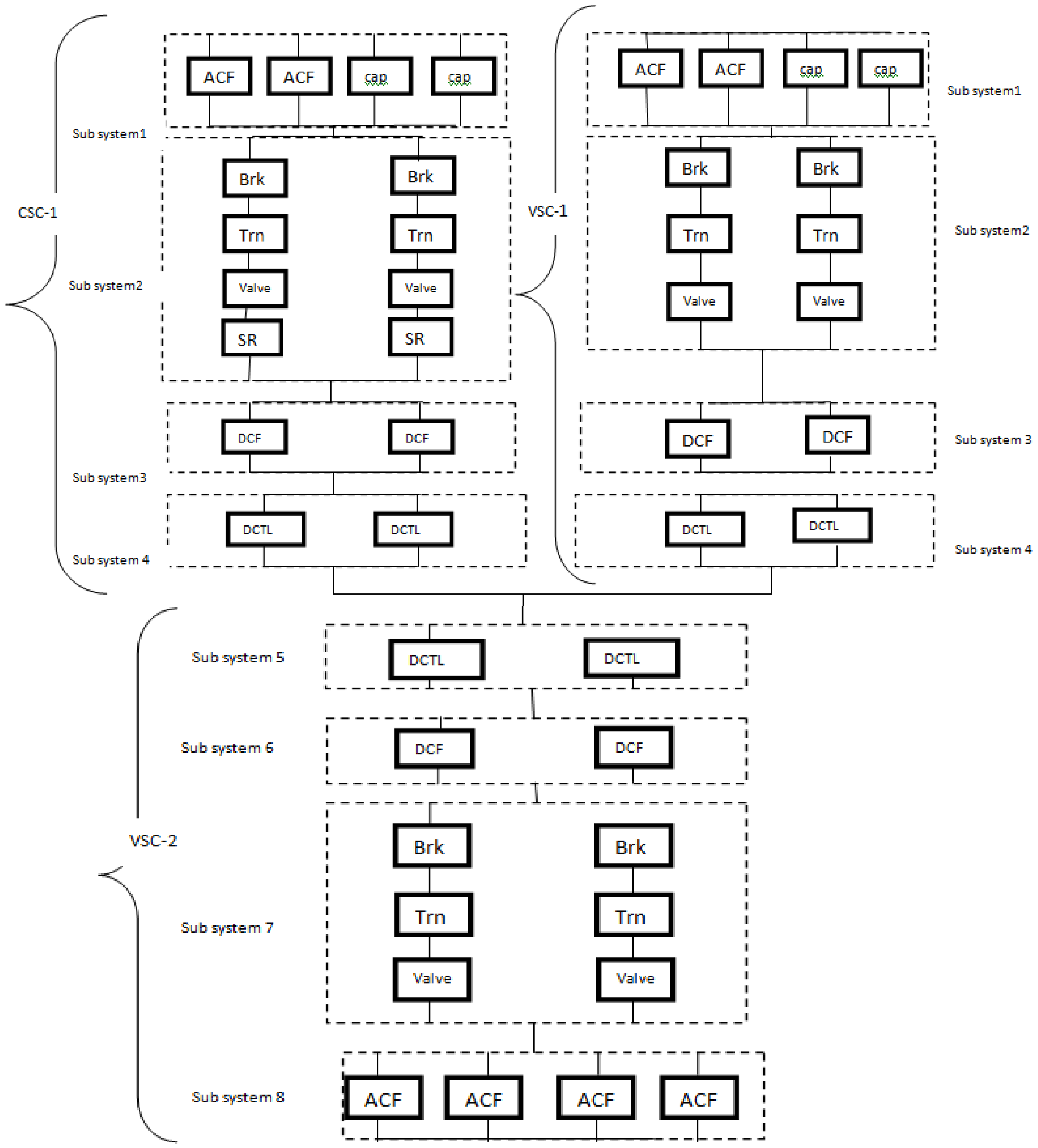

Fig 7 Comprehensive reliability model of combination of CSC and VSC multi terminal HVDC bipolar transmission system CSC converter used at bulk power source

$$\lambda_{-i} = \frac{x[i] * \lambda_{-i} + y[j] * \lambda_{-j}}{x[i] + y[j]}$$

(b) else if c = = 0 then

Z[i] = x[i] * y[j]

$$\lambda_{+i} = \frac{x[i] * \lambda_{-i} + y[j] * \lambda_{-j}}{x[i] + y[j]}$$

$\lambda_{-i} = 0$

(c) else z[i] = x[i] + y[j]

$$\lambda_{+i} = \frac{x[i] * \lambda_{-i} + y[j] * \lambda_{-j}}{x[i] + y[j]}$$

$$\lambda_{-i} = \frac{x[i] * \lambda_{-i} + y[j] * \lambda_{-j}}{x[i] + y[j]}$$

Step 4: display the array z[i]
Step 5: Assign the values of z[i] to x[i]
Step 6: go to step 2
Step 7: stop

Table 3 Equivalent reliability model of CSC

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_-[occ/yr]
1	0.9886724	0	3.163
0.9	3.3886E-6	1460	2.081
0.75	1.0725E-3	730	1.679
0.65	7.3081E-4	1460	2.619
0.62	2.905E-12	2920	2.083
0.6	2.5068E-9	2920	2.621
0.5	9.4849E-3	388.499	0.639
0.3	2.149E-15	4380	2.623
0	2.3107E-5	798.576	0

Similarly combining the sub systems 1 to 4 of VSC-1 of Fig 8, using the algorithm 4.1.1, the obtained equivalent reliability model of VSC-1 is as shown in Table 4. In Fig 7, sending end model is the combination of parallel connected CSC and VSC-1. Therefore combining the two reliability models of CSC and VSC-1 the obtained resultant model is Table 5.

Table 4 Equivalent reliability model of VSC-1

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_- [occ/yr]
1	0.9908114	0	3.069
0.9	3.39596E-6	1460	1.987
0.75	1.07716E-3	730	1.484
0.65	7.32392E-4	1460	2.525
0.62	2.9120E-12	2920	1.989
0.6	2.51210E-9	2920	2.527
0.5	7.35105E-3	313.499	1.6765
0.3	2.1541E-15	4380	2.529
0	1.40146E-5	667.19	0

Table 5 Equivalent model of combination of VSC-1 and CSC

Capacity	Probability	λ_-occ/yr	λ_+occ/yr
1	0.9795879	0	3.1159
0.9	1.15076e-11	1460	2.0339
0.75	1.155206E-6	730	1.5812

0.65	5.352400E-7	1460	2.571
0.62	8.46169E-24	2920	2.0359
0.6	6.29706E-18	2920	2.5739
0.5	6.972422E-5	355.751	1.0922
0.3	4.63028E-30	4380	2.575
0	3.23772E-10	748.967	0

The receiving end of Fig 7 consists subsystems 5 to 8 the reliability model of VSC-2 Table 6 is obtained by combining the subsystems 5 to 8 using the algorithm 4.1.1.

Table 6 Reliability model of VSC-2

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_- [occ/yr]
1	0.99086905	0	2.985
0.9	6.782127E-4	1460	2.235
0.75	1.087158E-3	730	1.585
0.6	1.741984E-7	2920	2.485
0.5	7.351058E-3	313.499	1.3925
0.3	1.98173E-11	4380	2.0485
0	1.387805E-5	645.032	0

The final COPT Table 7 is obtained by combing the reliability models Table 5 and Table 6.

Table 7 Final COPT of base case system

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_- [occ/yr]
1	0.9706433867	0	6.7635
0.95	1.15415336E-6	730	3.0872
0.9	6.78212785E-4	1460	0.2235
0.85	5.34723630E-7	1460	2.0974
0.82	8.4535335E-24	2920	2.6325
0.8	6.2909916E-18	2920	2.0945
0.75	1.08715944E-3	734.179	1.585
0.7	6.96569479E-5	313.499	3.5762
0.65	5.1644244E-10	4380	1.9704
0.62	8.1645232E-27	3957.16	1.08
0.6	1.7419848E-7	2920	2.485
0.5	7.35112537E-3	315.496	1.3925
0.3	1.9817381E-11	4380	2.0485
0.2	3.2345983E-10	6877.16	0.5904
0	1.38780545E-5	653.278	0

4.1.2 Numerical analysis: reliability indices are the indices which will predict the reliability of the system[14]. For Table 7, reliability indices of base case system at load level 0.8p.u capacity is evaluated as follows

Probability of failure Q = $\sum_{i\in s} p_i$ = 8.521993E-3

Where s = capacity below 0.75p.u

Frequency of failure F = $\sum_{i\in s} f_i = \sum_{i\in s} p_i(\lambda_i + \mu_i)$occ/yr = 3.14617 occ/yr

Expected Energy not supplied (EENS) = $\sum_{i\in s} p_i \times LC \times 8760 = 9.00473 MWhr/yr$

EDLC = $8760 \times \sum_{i\in s} p_i$ = 74.652 MW/yr

ELC = $\sum_{i\in s} LC_i \times f_i = 0.447223 hrs/yr$

Comprehensive reliability model of Multi terminal VSC (Fig 3) is obtained by replacing reliability model of CSC with VSC-1 reliability model. Therefore sending end model consists two parallel connected VSCs in parallel and receiving end with VSC-2. Where comprehensive reliability model of CSC and VSC multi terminal (Fig 3) is obtained by replacing the receiving end voltage source converter VSC-2 with reliability model of CSC. The same analysis and procedure 4.1 is applied to Fig 3 and Fig 4 the obtained reliability indices of three developing technologies at 0.8p.u capacity of load level are calculated and tabulated as shown in Table 8.

Table 8 Comparison between the reliability indices of three developing technologies

Indices	**CSC and VSC multi terminal with CSC converter used only at the bulk power source**	**Combination of CSC and VSC**	**Multi terminal VSC**
Q	**8.52199E-3**	**0.01568**	**8.50630E-3**
F (occ/yr)	**3.14617**	**5.52065**	**3.126**
EENS(MWhrs/yr)	**9.00473**	**27.827**	**8.96290**
EDLC(hrs/yr)	**74.652**	**137.39**	**74.515**
ELC (MW/yr)	**0.447223**	**1.154**	**0.44**

Table 8 and Fig 8(a-e) shows the reliability indices of three developed technologies of MTDC systems.

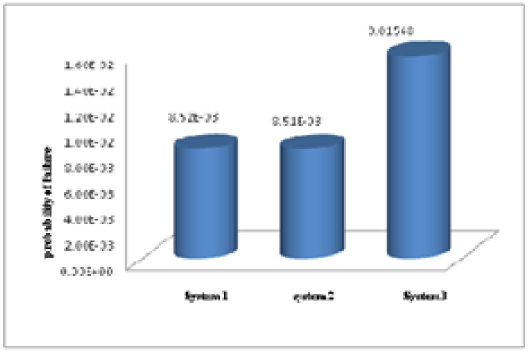

Fig 8 (a) probability of failure of three multi terminal developing technologies

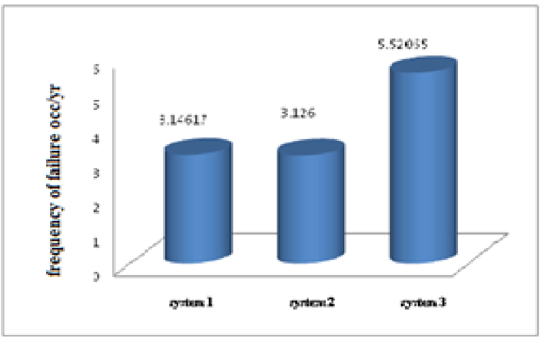

Fig 8 (b) frequency of failure of three multi terminal developing technologies

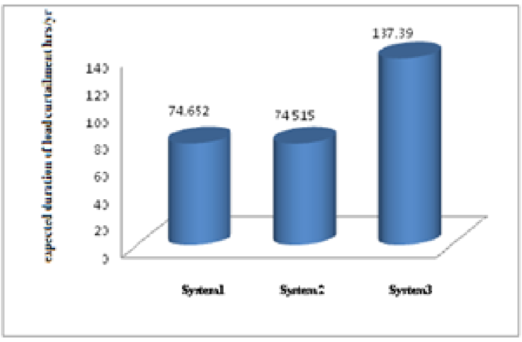

Fig 8 (c) expected duration of load curtailment of three multi terminal developing technologies

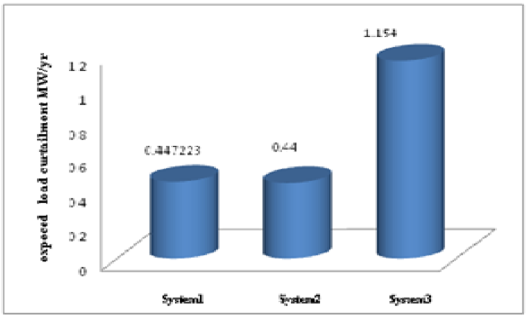

Fig8 (d) expected load curtailment of three multi terminal developing technologies

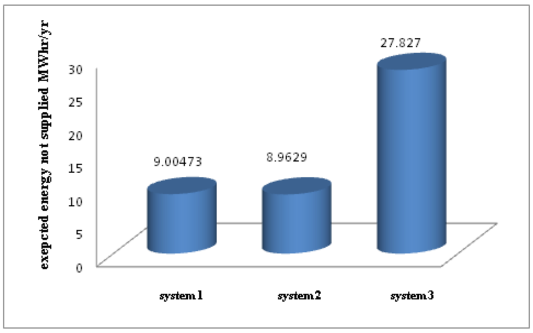

Fig 8 (e) expected energy not supplied of three multi terminal developing technologies

Fig 8(a)-Fig 8(e) shows the reliability indices of three developing technologies. From Fig8(a)-8(e). Comparing the reliability indices of three systems reliability indices of multi terminal VSC is more as compared with rest of the two systems. Because, CSC converters are less reliable than VSC converters and in the system 1 due to presence of two CSC converters at the each end of the HVDC causes more failures compared with the system2, which consists one CSC converter as a power source. Compared with System2, System3 is more reliable because of the usage of controllable characteristics of IGBTs in voltage source converters. Therefore multi terminal VSC is more reliable among the three developing technologies.

5. Conclusions:

Multi terminal DC systems are used, where huge power to be required for the transmission. Two types of HVDCs are used in multi terminal DC systems, one is thyristor operated(CSC-HVDC) and second is IGBT operated (VSC-HVDC). One of the advantages of VSC- HVDC is that it is naturally suited for building multi-terminal systems. This is due to the fact the DC voltage does not have to reverse in order to vary the direction of DC current and there are no control mode changes during the reversal. So each terminal can either supply or remove power to/from the VSC HVDC line without any difficult reconfigurations or DC side polarity reversing switches. In this paper types of multi terminal HVDCs and their reliability indices of three developing technologies of HVDC are discussed and compared. From that it is observed that among the three technologies multi terminal VSC is more reliable than the rest of the two technologies, because of IGBTs used in voltage source converters.

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