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Analysis and Improving Reliability Indices of VSC-HVDC transmission system tapped by a VSC- station

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***Abstract* – During the last three decades, reliability analysis of power systems considering transformers, breakers, transmission lines, and generators failure has been widely applied. This analysis has been done especially in the generation and transmission levels and is mainly restricted to high voltage alternating current (HVAC) systems. HVDC transmission systems are becoming increasingly popular when compared to conventional AC transmission. HVDC voltage source converters can offer advantages over traditional HVDC current source converter topologies and as such it is expected that HVDC-VSCs will be further exploited with the growth of HVDC transmission.**

In this paper, a comprehensive detailed reliability model of VSC-HVDC transmission system is developed, various reliability indices are calculated at the load point of the system and the impact of the VSC tapping station on these indices are illustrated.

***Keywords* – VSC-HVDC, reliability model, tapping station, reliability indices.**

1. Introduction

With the development of electrical network and the growth of electricity load, high voltage direct current (HVDC) transmission technology has been used because of its obvious superiority [1,2]. Now there are more than 60 HVDC projects, which are widely used in long-distance large capacity transmission, under ground cable transmission, submarine cable and regional network. Therefore the modern power systems have become composite power systems [5]. It is very important to study the influence of VSC-HVDC system to the reliability of the whole power system, and the methods about how to .evaluate the reliability of VSC-HVDC systems. The major difficulties evaluating the reliability of VSC-HVDC is how to establish the reliability models which can accurately simulate the DC systems. The models of DC systems are established by using markov analysis[3,4].

2. Reliability Model of VSC-HVDC System

VSC-HVDC bipole transmission system with 12-pulse IGBT converter, three phase one winding converter transformer the electrical wiring diagram is as shown in fig 1[6].

From the concept of reliability, the above system is obtained by the combination of series and parallel components. The reliability model of the above system is divided into four subsystems as shown in the fig 2(a).

Fig 2(b) shows the bipole system with tapping station. The entire system is divided into three major segments, namely, the sending end, the receiving end, and the tapping station. Also, each segment is divided into a number of subsystems to facilitate the modeling process. The procedure used to model the system is as follows.

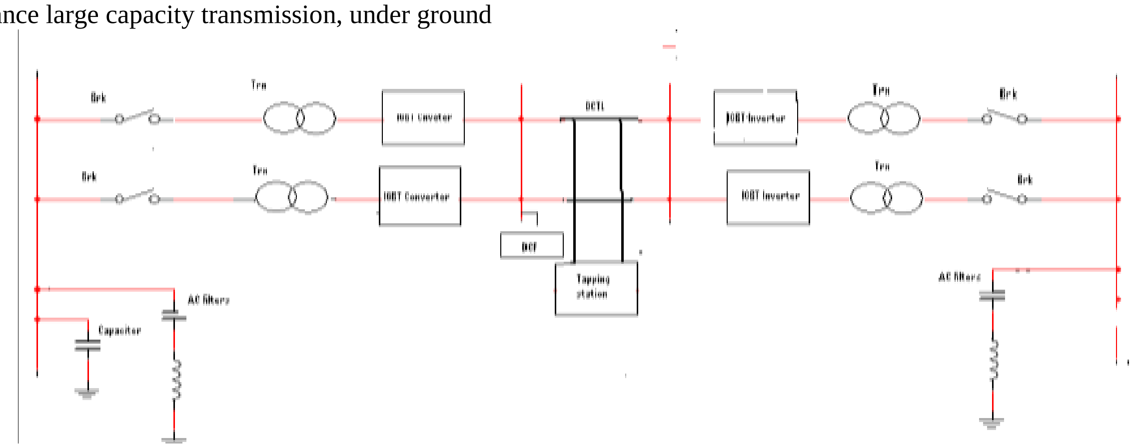

Fig. 1. VSC- HVDC transmission system with a VSC tapping station

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1: The reliability model associated with each segment is developed.
2: The reliability model of each segment is then developed by combining its subsystem models.
3: The reliability model of the whole system is obtained by combing the reliability models of the three segments.
4: The reliability indices are calculated using the final reliability model and the operational considerations[7].

2.1 Sending End: The sending end can be categorized into 4 subsystems. The subsystem 1 consists of ACFs, caps. second one consists of vlvs, Trn,Brk. third one consists of DCFs .fourth one consists of DCTLs. Each one these four subsystems is represented by an equivalent reliability model with up/down and one or more derated states. Each group of elements can therefore be considered as a single element in further modeling steps[13].

2.1.1 Subsystem 1: ACFs, caps are common among all poles and work in parallel with each other. A failure in more than one component will result in a reduction in the maximum transferable power. Different combination of available ACFs and caps can be considered and each combination produces a different level of sending end power. These ACFs and caps are represented by a single equivalent reliability model with some derated states[8,9].

2.1.2 Subsystem 2:vlvs,Trn and Brks are connected in series. These series elements can be combined using the approximated equivalent series method. Failure of any one of them causes the corresponding pole to be unavailable.

2.1.3 Subsystem 3: The DCFs are common can be used by all poles and therefore, they are modeled separately. Failure in each DCF reduces the maximum transferable power. The DCFs are therefore represented by a multistate model.

2.1.4 Subsystem 4: This subsystem includes the transmission lines between the sending end and tapping station. Since the outage of each line reduces the sending end capacity to 0.5pu. This model is in series with the equivalent models of previous subsystems.

2.2 Receiving End: From the converter point of view, the receiving end is analogous to the sending end, with relevant component reliability data and

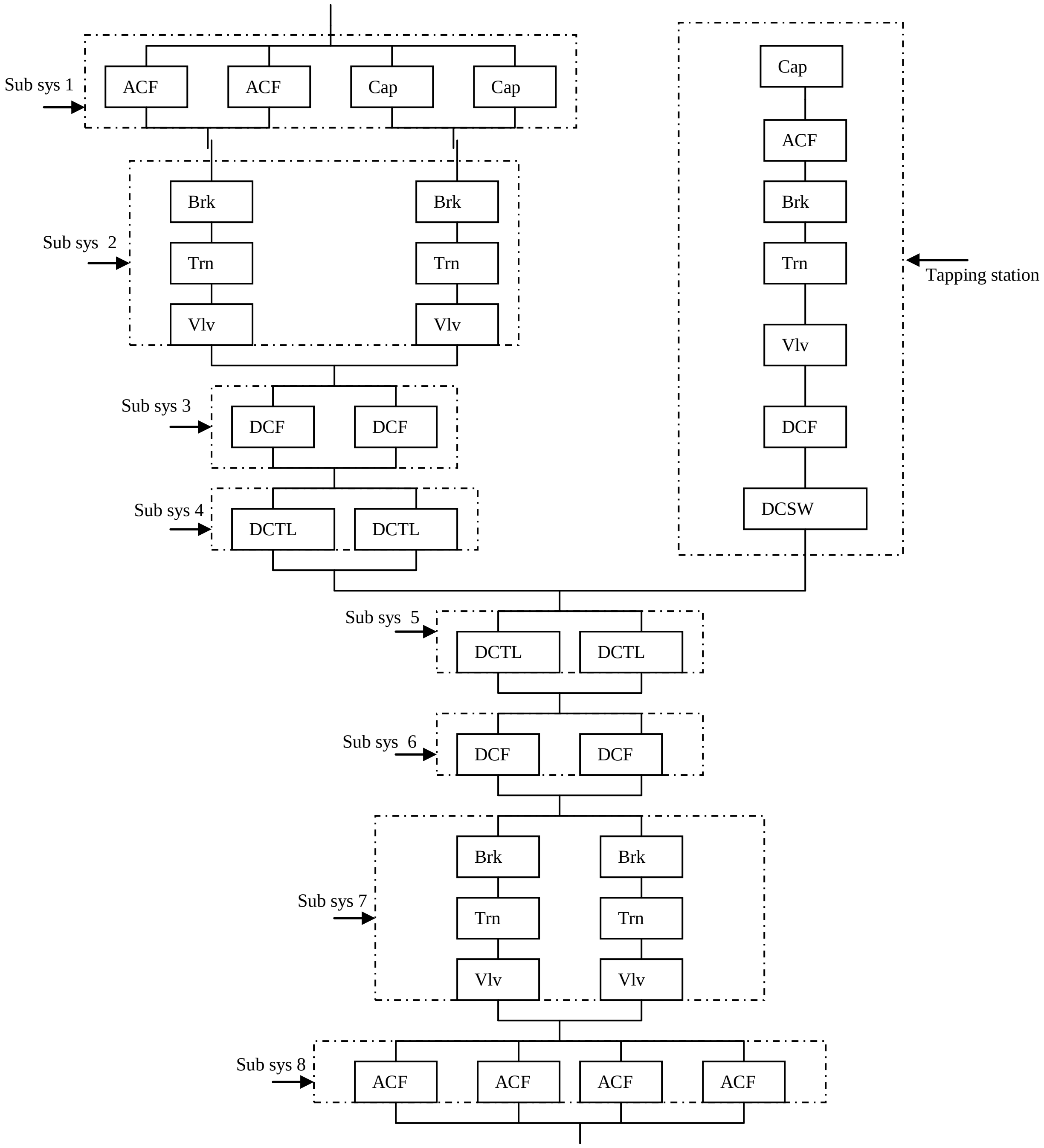

Fig.2. Comprehensive reliability model of VSC-HVDC transmission system

ACF: AC filters
Cap: reactive compensating capacitors.
Trn: converter transformer
Vlvs: power electronic switches IGBTs DCF: DC filters
DCTL: DC transmission line
DCSW: DC switch
Brk: Breaker.

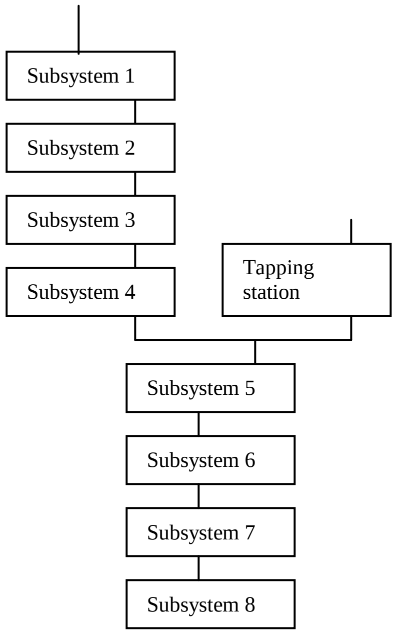

Fig 2(a) : compact reliability model of the whole system

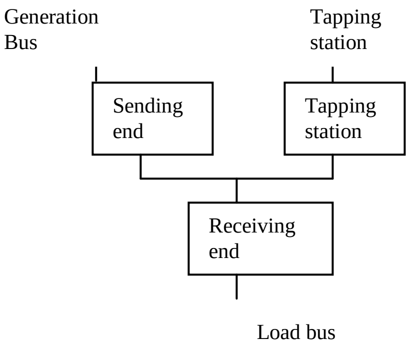

Fig 2(b) : Final equivalent reliability model of the whole system

Transmission line length. The reliability models for the subsystem components in the receiving end are therefore similar to those associated with the sending end. The reliability of subsystems 5,6,7,and 8 are similar to those of,4,3,2, and 1 respectively.

2.3 Tapping station: Tapping station is composed of vlvs, DCSWS, Brk, Trn, ACF, cap and DCF since a failure of any one of these components results in the failure of the entire tapping station. The reliability model is composed of series blocks as shown in the fig 3

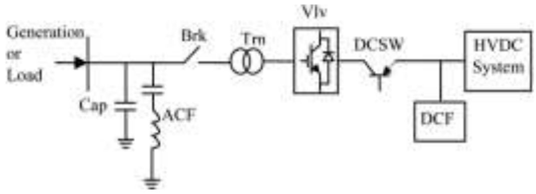

Fig. 3. configuration of VSC tapping station

3. Reliability Model of the Whole System and the Analysis Procedure

The reliability models associated with the sending end, the receiving end, and the tapping station are combined to obtain the reliability model of the entire system [11,12]. Fig 2 shows the detailed reliability model of the VSC-HVDC system of fig 1. Fig 2(a) and Fig 2(b) illustrate more compact models equivalent to the comprehensive model in Fig 2. In Fig 2(a) the components in each subsystem are combined and represented by an equivalent reliability model[8,9]. In Fig 2(b), all of the subsystems at the sending or the receiving ends are replaced with a single equivalent reliability model. This final model is used to determine the reliability indices of the system located at the receiving end.

3.1 Base case: The system shown in the Fig 1 is used to illustrate the operation of a VSC-HVDC transmission system with a VSC tapping station. The transmission capacity of the 500kV transmission system and generating capacity at the sending end are assumed to be 1200MW. The generating capacity on the ac side of the tapping station is 240MW and at the receiving end is assumed to be constant and is equal to 360MW. The length of the transmission line is 500km and tapping station is installed at the middle of the line (i.e 250km from each end). Reliability data for each component is provided in appendix I,II &III[10].

4. Description of Tables

The analysis procedure is based on the assisting unit approach. In the first stage, the reliability models of subsystems 1 to 8 are developed as shown in table 1. This table shows the probability of each state and the associated transition rates to the higher and lower available capacity levels. At the next stage, the models associated with subsystems 2 and 4 are combined as shown in table 2. This model is then convolved with the model of subsystems 3 as shown in table 3. At the next stage 2,3, and 4 are combined as shown in table 4. The final stage on the modeling of the sending end segment involves adding the model of subsystem 1 to the equivalent model of subsystem 2 to 4. The resulting model which represents the sending end is as shown in table 4.
COPT of the tapping station is givel in table 5 as assuming 0.2pu. Fully reliable generation capacity at the tapping station. The next stage involves adding the assistance of the tapping station to the COPT of the assisting system (table 4)the resulting COPT is shown in table 6. Note that table includes some states with the

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assistance capacity level of more than 1pu. The higher capacity of states is capped at 1p.u. of line capacity. Final stage is combined the COPT shown in table 7 with the reliability model of the receiving end segment which is identical to sending end except the subsystem 8, consists four ACFs are connected in parallel is as shown in the Table 6. The final COPT of VSC-HVDC bipole transmission system with tapping station as shown in table 8.

Table 1: reliability models associated with subsystems 1 to 8

subsystems	Capacity (p.u)	probability	λ_+ (occ/yr)	λ_- (occ/yr)
Subsystems2 &7	1	0.992643924	0	2..1
	0.5	7.3424981e-3	498.4	1.05
	0	1.35719500e-5	996.81	0
Subsystems3 &6	1	0.99890441	0	0.17
	0.5	0.00109529	2.054	0.085
	0	3Xe-7	4.108	0
Subsystems4 &5	1	0.99999144	0	0.8
	0.75	8.56e-6	730	0.4
	0	1.83e-11	1460	0
Subsystems1	1	0.999257249	0	1.0830
	0.9	3.427458e-6	876	1.0815
	0.65	7.3918406e-4	1460	0.543
	0.62	2.93905048e-12	1652	1.08
	0.6	2.53540568e-9	2336	0.5415
	0.3	2.1741141e-15	3112	1.0785
	0	1.36699e-7	2920	1.5e-3
Subsystems 8	1	0.9993153614	0	1
	0.9	6.844625762e-4	1460	0.75
	0.6	1.758037439e-7	2920	0.5
	0.3	2xe-11	4380	0.25
	0	8.591147e-16	5840	0

Table 2: reliability model associated with subsystems 2 & 4

Capacity (p.u)	probability	λ_+ (occ/yr)	λ_- (occ/yr)
1	0.992635427	0	2.270
0.5	7.3510581e-3	461.23	1.135
0	1.35779683e-5	922.46	0

Table 3: reliability models associated with subsystems 2, 3& 4

Capacity (p.u)	Probability	λ_+ (occ/yr)	λ_- (occ/yr)
1	0.9915479056	0	
0.75	1.087158332e-3	730	2.685
0.5	7.3510581e-3	458.448	1.1425
0	1.3877968e-5	1057.734	0

Table 4: reliability models sending end

Capacity (p.u)	Probability	λ_+ (occ/yr)	λ_- (occ/yr)
1	0.9908114324	0	3.088
0.9	3.39596457e-6	876	2.685
0.75	1.077168904e-3	730	1.1425
0.65	7.323920173e-4	1460	3.088
0.62	2.912044816e-12	1652	2.685
0.6	2.512108934e-9	2336	1.1425
0.5	7.3510581e-3	458.448	3.088
0.3	2.154137106e-15	3112	2.685
0	1.4014667e-5	1540.51	1.1425

Table 5: reliability model of tapping sattion

Capacity (p.u)	probability	λ_+ (occ/yr)	λ_- (occ/yr)
0.2	0.99903512	0	1.5525
0	0.00096488	`1037.16	0

Table 6: Reliability model of receiving end

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_-[occ/yr]
1	0.9908690536	0	2.985
0.9	6.782127851e-4	1460	2.235
0.75	1.087158332e-3	730	1.585
0.6	1.741984893e-7	2920	2.485
0.5	7.3510581e-3	313.499	1.3925
0.3	1.981738107e-11	4380	2.0485
0	1.387805421e-5	645.032	0

Table 7: reliability model of sending end associated with tapping station

Capacity (p.u)	probability	λ_+ (occ/yr)	λ_- (occ/yr)
1.2	0.9898554183	0	4.6215
1.1	3.3926878022e-6	1460	2.6345
1	9.560141349e-4	1037.16	3.069
0.95	1.076129565e-3	730	3.1375
0.9	3.27669827e-9	2497.16	1.082
0.85	7.316853466e-4	1460	1.1505
0.82	2.90925042e-12	2920	2.6325
0.8	2.50968505e-9	2920	0.905
0.75	1.039338732e-6	3650	1.585
0.7	0.007343965211	313.499	1.082
0.65	7.066704097e-7	5110	0.402
0.62	2.809773802e-15	3957.16	1.08
0.6	2.423883668e-12	3957.16	0.905
0.5	7.092888942e-6	4380	1.082
0.3	2.078483811e-18	5417.16	0.4705
0.2	1.400114453e-5	6877.16	1.5165
0	1.352247189e-8	1031.86	0

Table 8: Final COPT of the system

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_-[occ/yr]	Frequency [occ/yr]
1	0.98176778	0	6.654899	6.5335
0.95	1.05650e-3	730	3.1375	0.77456
0.9	6.78216e-4	1471.5	2.2349	0.99951
0.85	7.18345e-4	2190	1.1505	1.574
0.82	2.8561e-12	2920	2.6325	8.3476e-9
0.8	2.46392e-9	2920	0.905	7.19689e-6
0.75	1.08819e-3	732.788	1.585	0.79914
0.7	7.21006e-3	313.499	1.082	2.2681
0.65	6.93786e-7	5110	0.402	3.54246e-3
0.62	2.7585452e-15	3057.16	1.08	1.091898e-11
0.6	1.7420091e-7	2920.0144	2.48497	5.0910e-4
0.5	7.35815099e-3	317.418	1.3922	2.34585
0.3	1.9817383e-11	4380	2.0484	8.68407e-8
0.2	1.37458723e-5	6877.16	1.5165	0.09455
0	1.3891576e-5	645.408	0	8.96573e-3

5. Reliability Models of HVDC Transmission System

The techniques required for the reliability modeling of HVDC systems are same as those used for radial generation systems. An HVDC transmission system consists of numerous components, the failure of which results in a reduction in transmission capacity. It is impossible to include the models of all these components. A simpler procedure is to collect, the outage data of each component in series or parallel depending on the effect of their outages on the system reliability.

Series reliability structure: components in series reliability model are considered to be in series if the failure of any the component will failure the system. In Fig[3 .3] components Vlv, SR, Trn, DCF are connected in series reliability structure. The reliability data of the system is obtained by combining outage models of each of these components.

Parallel reliability structure: components are considered to be in parallel if failure of any one component will not cause failure of the system, it is working at a reduced capacity. The entire valve groups connected to pole is an example of the parallel structure. The HVDC transmission system reliability model consists of series parallel combinations of the reliability models of the components. The system reliability model can be simplified by block diagram reduction technique. Compact derivation can be used to obtain cumulative probabilities and frequency of various capacity states of the system [2].

6. Result Analysis

Forced outage data of each component is taken from APPENDEX-A and APPENDEX-B, Using frequency balance approach the reliability values of each component of HVDC are evaluated. From table 9 first column represents the reliability indices of VSC-HVDC without tapping station. Third column represents reliability indices with tapping station placed at the middle of the transmission line with 0.2 p.u capacity. From these two columns reliability indices are improved by placing tapping station in VSC-HVDC system. But the effects of tapping station on reliability indices are affected when the generation and transmission capacities are exceed the receiving end load. Accordingly, the existence of the tapping station would have no effect on the reliability indices of the receiving end the numerical results would be the same.

Table 9: Reliability indices of VSC-HVDC transmission system with and without tapping station

Index	Without tapping station	With tapping station	Percentage variation
Q	0.02060716	0.01568	23.8
F(occ/yr)	9.374	5.52065	41.1
EENS(MWhr/yr)	37.3311	27.827	25.4
EDLC(hr/yr)	180.518	137.39	23.89
ELC(MW/yr)	2.090	1.154	44.78

From the table 8 reliability indices of VSC-HVDC transmission system tapped by VSC tapping station at the middle of the transmission line with 0.2p.u. Capacity is calculated as follows

With tapping station:

Q = Probability of failure = 1- probability of success (or) reliability

For system with tapping station

$$Q = 1\text{-}R = 1\text{-}0.98176778 = 0.01568$$

Frequency of failure F

$$= P_s(\lambda_+ + \lambda_-)\ \text{[occ/yr]} = 5.52065$$

Where P_s be the probability of occurrence of the state and λ_+, λ_- is the upward and downward capacity departure rates respectively.

EENS : Expected energy not served $\sum_{i\in s} C_i F_i D_i = \sum_{i\in s} 8760 x C_i D_i$ [MW hr/yr] = 27.827MW hr/yr

EDLC : Expected duration of load curtailment PLCx8760 [hrs/yr] = 137.39 hrs/yr

ELC : Expected load curtailment $\sum_{i\in s} C_i F_i$ [MW/hr] = 1.154MW/yr

Without tapping station:

Q = Probability of failure = 1- probability of success (or) reliability

For system with tapping station

$$Q = 1\text{-}R = 1\text{-}0.979393 = 0.02060716$$

Frequency of failure F

$$= P_s(\lambda_+ + \lambda_-)\ \text{[occ/yr]} = 9.374$$

Where P_s be the probability of occurrence of the state and λ_+, λ_- is the upward and downward capacity departure rates respectively.

EENS : Expected energy not served $\sum_{i\in s} C_i F_i D_i = \sum_{i\in s} 8760 x C_i D_i$ [MW hr/yr] = 37.33MW hr/yr

EDLC : Expected duration of load curtailment PLCx8760 [hrs/yr] = 180.518hrs/yr

ELC : Expected load curtailment $\sum_{i\in s} C_i F_i$ [MW/hr] = 2.090 MW/hr

APPENDIX I

Component	Failure rate(f/yr)	Repair time In hrs	Installation time in hrs
ACF	0.54	6	-
Cap	0.0015	10	-
Vlv	0.5	4	45
Trn	0.05	1200	72
Brk	0.01	40	-
DCF	0.001	5	-
DCTL/km	3.00E-5	5	-
DCSW	1	4	-

APPENDIX II

Component out	Capacity(p.u)
All in	1
Only one cap	0.9
Only one ACF	0.65
Two caps	0.62
One cap and one ACF	0.6
Two caps and one ACF	0.3
Other combination	0

APPENDIX III

Component out	Capacity(p.u)
All in	1
Only one ACF	0.9
Two ACFs	0.6
Three ACFs	0.3
All out	0

CONCLUSIONS

The paper presented an evaluation methodology for the reliability of a VSC-HVDC transmission system with a VSC tapping station. The effects of a VSC tapping station on the reliability indices were presented. A comprehensive reliability model associated with a VSC-HVDC system with a tapping station was developed taking into account the impacts of different system components. The proposed model was simplified by using basic reliability engineering concepts. The result of the numerical analysis shows that a tapping station can significantly improve the reliability indices at the load point. The indices related to the energy and power (EENS and ELC) are affected more than the other indices related to the probability of failure.

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