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The Effect of Installation of Tapping Station on Interconnected AC/DC Transmission Systems

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Abstract: The effect of tapping station on interconnected AC/DC transmission system is presented in this paper. Reliability values of AC and bipolar VSC-HVDC transmission systems are developed by using Markov modelling. The reliability indices are evaluated by DC line without tapping station and with tapping station. Reliability models of bipolar VSC-HVDC and AC systems are developed. A contingency enumeration technique with equivalent approach is used to determine the reliability indices.

Keywords: Tapping station, VSC-HVDC, reliability indices, enumeration technique.

I INTRODUCTION

Operation of DC links in parallel with AC lines has economical and technical advantages of supplying intermediate loads located between the sending and receiving ends through the AC facilities[1]. The first step in calculating the reliability of HVDC transmission systems by developing the appropriate models for all the components in the system[3,5] . The reliability model of DC line and AC lines are combined by a contingency is defined as a combination of generating unit and transmission line outages [2].

This paper examines the effect of tapping station on interconnected AC/DC line. A wide range of reliability indices are calculated at load level without and with tapping station on DC link.

II TEST SYSTEM

The system used for investigations described in the paper as shown in Fig 1. It consists two load points L_1 and L_2 connected by a AC/DC transmission lines each load point with different peak load values [7].

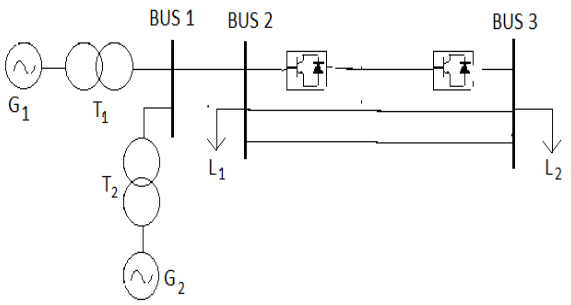

Fig 1 interconnected AC/DC transmission lines

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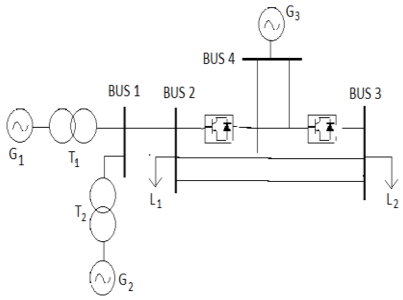

Fig 2: interconnected AC/DC tapped by a tapping station

Fig 2 shows the interconnected AC/DC transmission system tapped by a VSC tapping station represented by G3. In this paper comparing the reliability indices of Fig 1 and Fig 2 and the effect of tapping station on interconnected system is investigated.

III METHODOLOGY

In this paper the basic Markov modelling approach is used to take account the distribution of component failure over time. It is possible to compute the reliability parameters as the long term probability of the system being in a given state by solving a linear differential equations of the system. The graphical model constructed to display all possible transition paths between states is called state space diagram[6].

A Markov model can be applied to systems whose random behaviour varies either discretely or continuously with time. In this paper Markov modelling has been adapted. fig 3 shows a basic example of two state system.

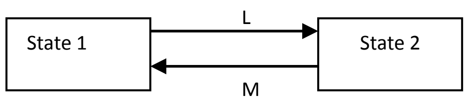

Fig 3 state space diagram of two state Markov modelling

In Fig 3 there are two states up state (state 1) and down state (state 2). There are two transitions associated with each component, the first L representing the failure process and the second M representing the repair process [10,11]. This model implies that the component becomes operational and in service immediately following the repair acting. The duration of the failure is limited to the time it takes to install the spare unit rather than to repair of the equipment itself.In this paper, only the equations for calculating the steady state solution of the system are presented. This solution gives the probability of being in a certain state after an infinite time in the system. It can be shown that this steady state solution can be found by solving the eqn 1.

$$PQ = 0 \ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$\sum P_i = 1$$

Here P_i is a row vector and

Q = transition rate matrix for the Markov Process

$$= \begin{pmatrix} P_{11} & P_{12} \ldots\ldots\ldots\ldots\ldots\ldots P_{1n} \\ P_{21} & P_{22} \quad \ldots\ldots\ldots P_{2n} \\ \ldots\ldots\ldots\ldots\ldots\ldots & \\ P_{n1} & P_{n2} \quad \ldots\ldots\ldots\ldots P_{nn} \end{pmatrix} \ldots.2$$

In this matrix P_{ij} is the transition rate from state i to state j. The diagonal element P_{ii} are defined in the eqn 3.

$$P_{ii} = 1 - \sum P_{ij} \ldots\ldots\ldots\ldots\ldots\ldots 3$$

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Consider the half capcity states or repair process of the component another one more state is included to the state model Fig 3 is converted into three state model as shown in Fig 4. In Fig 4 State 3 is known as repairable state.

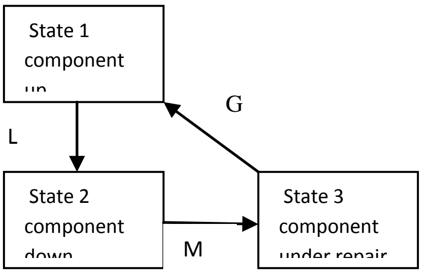

Fig 4: state space diagram of three state Markov modelling

IV COMPONENT RELIABILITY MODEL

availability and reliability of any system depending upon the Performance of each component within the system. The failure rate and repair time of
individual components are therefore essential parameters in evaluated the system reliability [5].Using Markov modelling the reliability values of each component of the system is evaluated. The reliability models associated with some of the components of Fig 1 are illustrated in the following section [9].

A Generating unit model

All the generating units are represented by two or three states. Fig 3 shows a state model of generating unit in which state 1 is the operating state with a maximum capacity available or in the down state 2 with a zero capacity. Large modern generating plants consists large quantity of auxiliary equipment. In Such a case failure of any one does not completely shutdown, it can operated at a reduced output level. This concept is known as a partial output state or reduced state of a unit.
The modified generating unit three state model is as shown in the Fig 4. State 1 is maximum capacity level, state 2 is half capacity level, state 3 is a zero capacity level. The reliability model of generating unit capacity outage table is as shown in the table 1.

B Transmission lines

AC transmission lines and the transformers are represented by a two state model as shown in the fig 3. The capacity outage table of two line AC transmission system is as shown in table 2 The reliability model associated with voltage source converter HVDC transmission system is as shown in the Fig 5. In Fig 5 AC side of the rectifier each pole has a capacitor (Cap) and bank of filters (ACFs) these elements are placed in parallel and associated reliability model is as shown in table 3. The AC side inverter consists four banks of AC filters, placed in parallel in the model. The associated capacities of four ACFs are as shown in table 3. Each pole of HVDC consists smoothing reactor (SR), Breakers (Brk), Transformers (Trns) and Valves (Vlvs). Two poles are placed in parallel in the model [ ] . The forced outage data associated with the reliability model of HVDC is shown in Fig 5 are given in APPENDEX-B. Using the given data the capacities associated with the bipolar DC link is as shown in table 3.

C Tapping station

The components of the tapping station consists VlVs, Brk, Trn, ACFs, DCFs, and DCSW. The schematic diagram of tapping station is as shown in the Fig 6. And the corresponding reliability model of tapping station is shown in the Fig 7 [12].

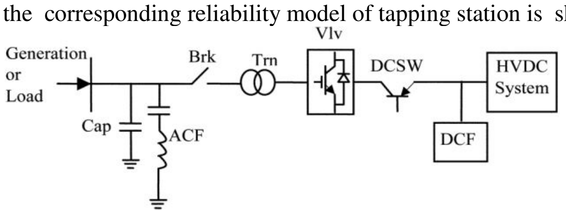

Fig 6 configuration of VSC tapping station

Tapping station has series connected components, 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 Fig 7. reliability model of tapping station is as shown in table 4 [13].

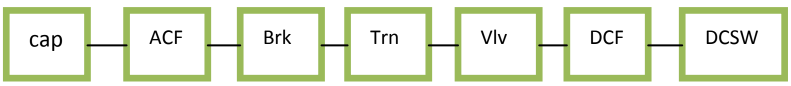

Fig 7: reliability model of tapping station

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V ANALYSIS AND PROCEDURE

Reliability values of each component of AC and DC lines are evaluated by Markov modelling two state or three state models. For components which has large repair time such as converter, converter transformers and reactors are considered three states as shown in fig 5. Each reliability model of HVDC table 3 are cumulated one by one by contingency enumeration technique to get the final COPT of the HVDC .The test system consists two areas A and B interconnected through two AC lines and bipolar DC line[8]. The reliability indices are calculated by using contingency enumeration technique. The number of contingencies increases, as the number of components in the system are increased. One way to reduce the computation time and to consider more possible cases is to use a reduction technique to determine the equivalent model for each area up to load points 1 and 2 equivalent model at bus 3 is determined by combining the generating unit and transmission lines both AC and DC units.

VI DESCRIPTION OF TABLES

In first step combine the reliability models of two parallel AC line (table 2) with the DC link without tapping station is as shown in table 5 obtained equivalent model obtained model is as shown in table 6. In second step combine equivalent model of table 2 with the reliability model of DC link with tapping station as shown in table 7 obtained final COPT is as shown in table 8. Comparing the tables 6 and table 8 reliability indices are evaluated at 0.8p.u load level by using cumulative probability approach. Comparison between the reliability indices of interconnected system without and with tapping station is as shown in table 9.

Table 1
Generating unit reliability model

Capacity p.u	Capacity in MW	probability	λ_+(occ/yr)	λ_-(occ/yr)
1	1600	0.9021463		
0.5	800	0.0947492		
0	0	0.0031045		

Table 2
Double line HVAC reliability model

Capacity p.u	Capacity in MW	Probability	λ_+(occ/yr)	λ_-(occ/yr)
0.167	200	0.983094134	10	0
0.833	100	0.016833804	5	584
0	0	7.20625E-5	0	1168

Table 3
Reliability models associated with subsystems 1 to 8

Subsystems	Capacity[p.u]	probability	λ_+[occ/yr]	λ_-[occ/y/r]
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	0.992643924	0	1.17
	0.5	7.3424981E-3	313.5	0.585
	0	1.35779500E-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
8	1	0.9993153614	0	1
	0.9	6.84462576E-4	1460	0.75
	0.6	1.75803743E-7	2920	0.5
	0.3	2xE-11	4380	0.25
	0	8.591147E-16	5840	0

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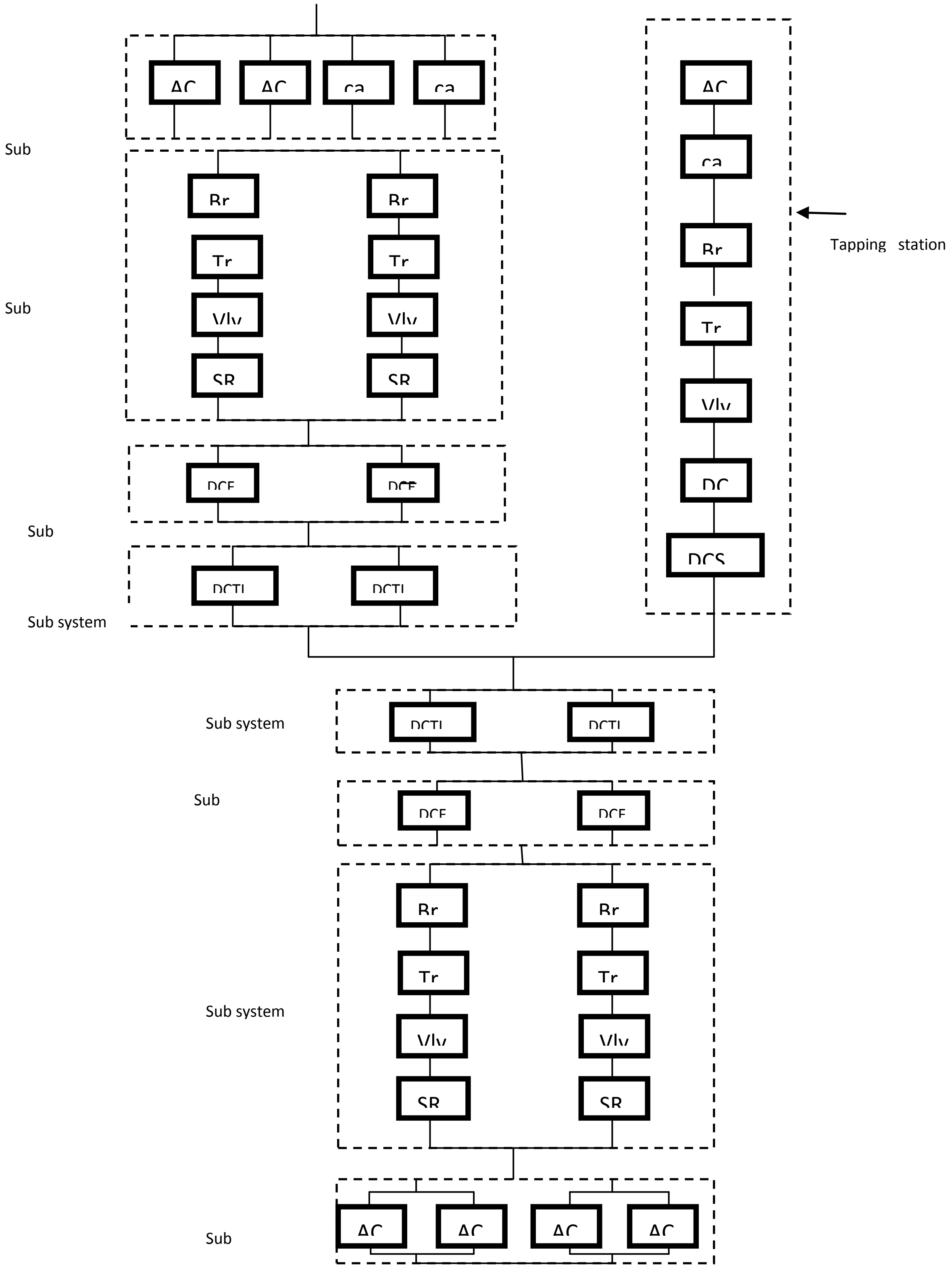

Fig 5 Comprehensive reliability model of VSC-HVDC bipole transmission

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Table 4

COPT of tapping station

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_-[occ/yr]
0.2	0.99903512	0	1.5525
0	0.00096488	1037.16	0

.

Table 5

Reliability model of VSC-HVDC without tapping station

Capacity	Probability	λ_-occ/yr	λ_+occ/yr	Frequency
1	0.981764386	0	3.0119	
0.9	6.816087E-4	1460	2.234	0.99667
0.75	2.164327E-3	730	1.535	1.58328
0.65	7.323920E-4	1460	2.525	1.07114
0.62	2.91204E-12	2920	1.989	8.5089e-9
0.6	1.767105E-7	2920	2.485	5.1643E-4
0.5	0.01470E-11	313.49	1.3925	4.62957
0.3	1.98195E-11	4380	2.0485	8.6850E-8
0	2.789272E-5	656.16	0	0.018302

Table 7

Reliability model of VSC-HVDC with tapping station

Capacity[p.u]	Probability	λ_+[occ/yr]	λ_- /[occ/yr]	Frequency [occ/yr]
1	0.981767748	0	6.654899	6.5335
0.95	1.056509E-3	730	3.1375	0.77456
0.9	6.782160E-4	1471.5	2.2349	0.99951
0.85	7.183455E-4	2190	1.1505	1.574
0.82	2.85619E-12	2920	2.6325	8.347E-9
0.8	2.463924E-9	2920	0.905	7.196E-6
0.75	1.088197E-3	732.788	1.585	0.79914
0.7	7.210068E-3	313.499	1.082	2.2681
0.65	6.937862E-7	5110	0.402	3.5424E-3
0.62	2.75854E-15	3057.16	1.08	1.092E-11
0.6	1.742009E-7	2920.01	2.4849	5.0910E-4
0.5	7.358150E-3	317.418	1.3922	2.34585
0.3	1.98173E-11	4380	2.0484	8.6840E-8
0.2	1.374587E-5	6877.16	1.5165	0.09455
0	1.389157E-5	645.408	0	8.9657E-3

VII EVALUATION PROCEDURE

In base case system transferring capacity of two parallel connected HVAC is 200MW capacity is considered as 0.167p.u and VSC-HVDC bipole link capacity 1200MW is taken as 1p.u base case. Generating power 1600MW as 1.167p.u, with load levels L_1 with 200MW (0.167p.u) and L_2 with 960MW(0.8p.u)[ ]. Combining the reliability models of transmission line table 2 and VSC-HVDC bipole link model table 5 obtained equivalent model is as shown in table 6. In equivalent model first condition is the case in which all the components in the system are operating is considered as 1p.u. The same transferring capacity of the each line is combined as equivalent capacity level. Example o.5p.u capacity of generating state is combined with 0.5p.u capacity of line state. Reliability indices at load point L_2 at 0.8p.u are calculated from table 6 by adding the states below 0.8p.u capacity.
From table 6

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Table 6

Equivalent model of Two parallel connected HVAC & bipole VSC-HVDC Without tapping station

Capacity p.u	Probability	λ_+(occ/yr)	λ_-(occ/yr)
1.167	0.9651668088	13.0911	0
1	7.0748396e-5	3.0911	1168
1.067	6.70085562e-4	10.8571	1460
0.917	2.127737404e-3	11.5561	730
0.817	7.20010288e-4	10.5661	1460
0.787	2.862814161e-12	11.1021	2920
0.767	1.737231523e-7	10.6061	2920
0.667	0.0144535581	11.6986	313.499
0.467	1.94844686e-11	11.0426	4380
0.167	2.74211704e-5	10	656.165
0.9833	0.0165268292	2.766	2044
0.833	1.1474068e-5	3.465	1314
0.733	1.232894355e-5	1.237	2774
0.703	4.90207914e-14	3.011	3504
0.6833	2.974711571e-9	2.515	3504
0.5833	2.474924381e-4	1.003	4964
0.3833	3.336381676e-13	8.6171	5840
0.0833	4.695404132e-7	1.9089	1240.165
0.9	4.911843047e-8	5.325	2628
0.75	1.55966831e-7	2.475	1898
0.65	5.27779992e-8	0.241	3358
0.62	2.098492284e-16	5.0801	4088
0.6	1.273420747e-11	5.5761	4088
0.5	1.059470802e-6	0.667	5548
0.3	1.428245241e-15	0.867	6424
0	2.010019207e-9	0	1824.165

Probability of failure Q = $\sum_{i \in s} p_i = 0.014742$

Where s = state capacity below the 0.8p.u

Similarly frequency of failure is evaluated by cumulating the individual frequency failure of each state from 0p.u to 0.75p.u.of table 4.17.

Frequency of failure F = $\sum_{i \in s} f_i = \sum_{i \in s} p_i (\lambda_i + \mu_i)$ occ/yr = 5.988 occ/yr

Expected energy not supplied is obtained probability of each state with load curtailment at that state and number of hours per year.

Expected Energy not supplied (EENS) = $\sum_{i \in s} p_i \times LC \times 8760 = 64.865 MWhr / yr$

Expected duration of load curtailment is evaluated by multiplying cumulative probability of at that required capacity level with number of hours per year.

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EDLC $= 8760 \times \sum_{i \in s} p_i$ = 129.319 hrs/yr

Expected load curtailment is obtained by cumulating the product of individual frequency per failure of each capacity with load curtailment at that state.

ELC $= \sum_{i \in s} LC_i \times f_i = 3.1009 MW / yr$

Table 8

Reliability model of VSC-HVDC with tapping station

Capacity p.u	Probability	λ_- (occ/yr)	λ_+ (occ/yr)
1.167	0.965170114	16.654899	0
1.117	1.038648095e-3	13.517399	730
1.067	6.667502319e-4	15.504399	1471.5
1.017	7.062008294e-4	12.366899	2190
1	1.365672755e-5	6.654899	1168
0.987	2.807906712e-12	14.01649	2920
0.967	2.422273006e-9	15.74399	2920
0.917	1.069800747e-3	15.06399	732.788
0.867	7.08817574e-3	14.59349	313.499
0.817	6.820571599e-7	13.59349	1043.499
0.787	2.711909701e-15	13.105581	5110
0.767	1.712558959e-7	13.44299	2920.0144
0.667	7.233755074e-3	12.29249	317.418
0.467	1.948235313e-11	11.381581	4380
0.367	1.351348626e-5	10.231081	6877.16
0.167	1.365672755e-5	9.320172	645.408
1.033	1.778507048e-5	1.8625	1314
0.9833	1.141695625e-5	3.8495	2044
0.933	1.20924802e-5	0.712	2785.5
0.9033	4.808059544e-14	7.805399	2639.5
0.8833	4.147727833e-11	4.08909	3515.5
0.8333	1.831850631e-5	0.4385	2785.5
0.7833	1.213728747e-4	2.93859	4987
0.7333	1.167906119e-8	0.712	4257
0.7033	4.643681087e-17	6.89449	5559.5
0.6833	2.932464029e-9	1.78809	1627.499
0.5833	1.238656716e-4	0.63759	3098.99
0.3833	3.336019437e-13	0.273319	1940.998
0.2833	2.313953172e-7	0.877181	3412.498
0.95	7.613470143e-8	9.792399	1898
0.9	4.887394495e-8	7.805391	2628
0.85	3.176574197e-8	10.9428	3369.5
0.82	2.058244174e-16	3.849508	3233.5
0.8	1.775568e-13	7.565809	4099.5

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0.75	7.841824467e-7	9.7923	3369.5
0.7	5.195755387e-7	6.415307	5571
0.65	4.999596924e-11	8.6418	4841
0.62	1.987876702e-19	2.769008	6143.5
0.6	1.255335331e-11	5.264809	2211.499
0.5	5.30246755e-7	4.114309	3682.99
0.3	1.428090173e-15	3.2034	2524.998
0.2	9.905619104e-10	2.0529	3996.499
0	1.001061745e-10	0.9024	0

From table 8

Probability of failure Q = $\sum_{i \in s} p_i$ =7.38479E-3

Where s = state capacity below the 0.8p.u

Similarly frequency of failure is evaluated by cumulating the individual frequency failure of each state from 0p.u to 0.75p.u.of table 4.17.

Frequency of failure F = $\sum_{i \in s} f_i = \sum_{i \in s} p_i(\lambda_i + \mu_i)$ occ/yr = 2.876 occ/yr

Expected energy not supplied is obtained probability of each state with load curtailment at that state and number of hours per year.

Expected Energy not supplied (EENS) = $\sum_{i \in s} p_i \times LC \times 8760 = 32.538 MWhr / yr$

Expected duration of load curtailment is evaluated by multiplying cumulative probability of at that required capacity level with number of hours per year.

EDLC $= 8760 \times \sum_{i \in s} p_i$ = 64.690 hrs/yr

Expected load curtailment is obtained by cumulating the product of individual frequency per failure of each capacity with load curtailment at that state.

ELC $= \sum_{i \in s} LC_i \times f_i = 1.50392 MW / yr$

Similarly combing the table 7.3 with reliability model of HVDC with tapping station, table 7.7 obtained equivalent reliability model is represented by table 7.8. Reliability indices at load point L_2 are calculated from the table 7.8.

VIII RESULTS AND DISCUSSION

Due to generating unit deficiency or fault in any DC line does not meet the load demand at load point L_2. Due to fault in any AC line or two AC lines will not affect the load demand at the load point L_1. In such a case DC bipole transmission system is tapped by a tapping station with 0.2p.u capacity value, which will compensate the load curtailment at the load point L_2 and meet the load demand.

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Table 9

Comparison between the reliability indices at load point L_2 without and with tapping station

Capacity p.u	Without tapping station	With tapping station
Q	0.014742	7.38479E-3
F(occ/yr)	5.988697	2.876935
EENS (MWhr/yr)	64.865	32.538
EDLC (MW/yr)	129.319	64.690
ELC (hrs/yr)	3.10096	1.50392

From the results table 9 probability of failure is reduced from 0.014742 to 7.38479E-3 with % reduced by installation of tapping station on AC/DC interconnected system. Similarly frequency of failure is 5.98869occ/yr to 2.8769occ/yr with reduced percentage of % , expected duration of load curtailment from 129.319MW/hr to 64.690MW/hr with %. Expected energy is not supplied from 64.865MWhr/yr to 32.538MWhr/yr with %. Expected load curtailment is 3.10096hrs/yr to 1.5092hrs/yr with % are reduced by installation of tapping station on interconnected AC/DC transmission system. Comparing the reliability indices of two cases of table 9 all indices are reduced by 50% by provision tapping station on of DC link of interconnected AC/DC transmission system. Hence provision of DC link with tapping station improves the reliability indices.

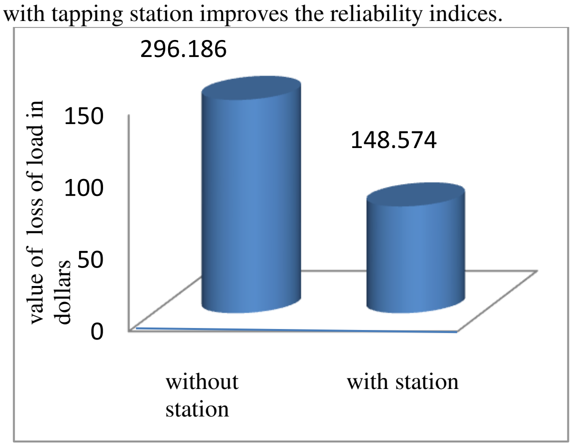

Fig 6 impact of tapping station on interconnected AC/DC value of loss of load

From table 6 expected energy not supplied (EENS)

Without tapping station is 64.865MWhr/yr

$$\text{EENS in MW} = \frac{64.865}{(24 \times 365)} = 0.00740468 \text{ MW}$$

$$\textbf{VOLL} = 40 \times 0.00740468 = 296.186 \text{ \$}$$

With tapping station is 32.538MWhr/yr

$$\text{EENS in MW} = \frac{32.538}{(24 \times 365)} = 0.0037143835 \text{ MW}$$

$$\textbf{VOLL} = 40 \times 0.0037143835 = 148.57 \text{ \$}$$

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Fig 6 shows the value of loss of load of interconnected AC/DC system without and with installation of tapping station. From Fig 6 it is observed that value of loss load, DC link with installation of tapping station is reduced to 147.616$ as compared with the DC link without tapping station.

IX CONCLUSIONS

Interconnection of HVDC transmission system with HVAC improves the reliability, transmit the bulk amount of power to load. Tapping stations are share the load whenever the load demand exceeds the generating capacity. In this paper the effect of installation of tapping station on reliability of interconnected AC/DC lines are investigated and compared.

From this it will be concluded that the effect of installation of tapping station improves the reliability indices as compared to without installing the tapping station.

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