HVDC Transmission Placement Study to Increase Critical Clearing Time Using Sensitivity Analysis

I Gede Dyotha Yogadipha Bagas
Department of Electrical Engineering
Institut Teknologi Sepuluh Nopember
Surabaya, Indonesia
dyotha.yogadipha@gmail.com

Ardyono Priyadi
Department of Electrical Engineering
Institut Teknologi Sepuluh Nopember
Surabaya, Indonesia
priyadi@ee.its.ac.id

Vita Lystianingrum
Department of Electrical Engineering
Institut Teknologi Sepuluh Nopember
Surabaya, Indonesia
vita@ee.its.ac.id

***Abstract*— Stability is the ability to return to normal conditions after a disturbance. High Voltage Direct Current (HVDC) transmission can solve voltage stability problems that occur in ac systems, reduce the failure current, and increase the reserve of electric power. Time Domain Simulation (TDS) is a popular method for calculating Critical Clearing Time (CCT). To calculate load flow sensitivity, use the load flow sensitivity analysis command in Powerfactory 15.1. The variable considered in this research is dφ/dP. This research is concerned with increasing the CCT value in the most optimal AC/DC transmission system based on the sensitivity analysis method. By taking several samples that have high sensitivity values, namely line 8-9 to 7-8 with an average cct change value of 0.555 s, medium values, line 5-8 to 9-6 have an average cct change of 0.234 s, and low from line 6-4 to 9-4 with an average change of 0.109 s. The data above shows that a channel with a large sensitivity value will provide a higher increase in cct value compared with a low sensitivity value when paired with an HVDC.**

Keywords*— *critical clearing time (cct), high voltage direct current, sensitivity analysis, transient stability.

I. INTRODUCTION

Transient stability has an important role in maintaining system protection, such as determining whether the system remains stable or not after a major disturbance. These disturbances can be in the form of sudden load changes, disturbances to generators, disturbances to transmission lines, and so on.

High Voltage Direct Current (HVDC) transmission is a type of electricity transmission using high voltage direct current as the source. HVDC has many benefits compared to High Voltage Alternating Current (HVAC) under certain conditions, including efficient and relatively stable power losses with the same power rating.

Time Domain Simulation (TDS) or parameter sensitivity, to calculate CCT [1]. Numerical simulation or Time Domain Simulation (TDS) is a popular method for calculating Critical Clearing Time (CCT). This method is known as the most accurate method because the calculation uses numerical integration of the specified initial conditions.

Load flow sensitivity analysis is used to determine the voltage stability of a network. The sensitivity method can be used to determine the state variable solution relationship of the differential equation during severe disturbance, stability limits, critical engine acceleration area and deceleration area with respect to power changes and transformer ratio changes [2].

II. METHODS

A. *Transient stability*

Transient stability is the ability of the system to maintain a synchronous state after a sudden major disturbance. Transient stability involves shifting the angle of the generator rotor so that the transient stability is included in the stability of the rotor angle. Electromechanical oscillations in electric power systems are closely related to the problem of rotor angle stability. The fundamental factor that causes the stability of the rotor angle is the power output of the synchronous generator which differs from each other when the rotor is isolated. The power flowing from the generator to the motor is a function of the angle (δ) between the rotors of the two machines. The difference in angle is caused by the internal angle of the generator, the internal angle of the motor, and the difference in angle between the terminal voltage of the generator and the motor. The greater the value of the rotor angle, the power to be distributed will increase to a maximum when the angle is 90^o.

B. *High Voltage Direct Current*

HVDC is a type of electricity transmission using high voltage direct current. HVDC has many benefits compared to HVAC or under certain conditions. HVDC consists of transmission poles, conductors, insulators, and terminal equipment. DC lines can carry as much power with two conductors as AC lines with three conductors of the same size. *Therefore,* for a given power level the DC line requires a smaller and simpler RoW (Right of Way). Broadly speaking, HVDC links are classified into three categories, monopolar link, bipolar link, and homopolar link [3].

C. *Power Flow Sensitivity Analysis*

To determine the magnitude of the relative voltage correction and vector angle to the active and reactive power vectors, a power flow sensitivity analysis is proposed using power flow studies as in [4]. The Jacobian matrix is used to determine the sensitivity analysis index. The relationship between the Jacobian matrix and the power equation can be written as [5].

$$\begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \partial\delta_i \\ \partial|V|_i \end{bmatrix} = \begin{bmatrix} \partial P_i \\ \partial Q_i \end{bmatrix} \quad (1)$$

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III. Results and Discussion

Researchers used DigSilent Power Factor 15.1 software to carry out simulations related to research. The research object of this research is the 9 bus transmission system with 3 generators and the 14 bus transmission system with 5 generators. In the early stages of the research, the researcher looked for dφ/dP, dφ/dQ (written as dphi/dP, dphi/dQ in Powerfactory 15.1), dV/dP and dV/dQ using sensitivity analysis. Next, look for the critical clearing time (cct) value for each bus at the initial conditions and when the HVDC channel has been installed. After all the data has been collected, an analysis is carried out to what extent is the relationship between the dφ/dP value to changes in the cct value from the initial conditions and after the HVDC channel is installed on each possible existing bus.

A. *Transmission System*

The system used to conduct research in this thesis is a system of 9 buses 3 generators and 14 buses 5 generators. All systems used are available in the DigSilent Power Factor 15.1 software.

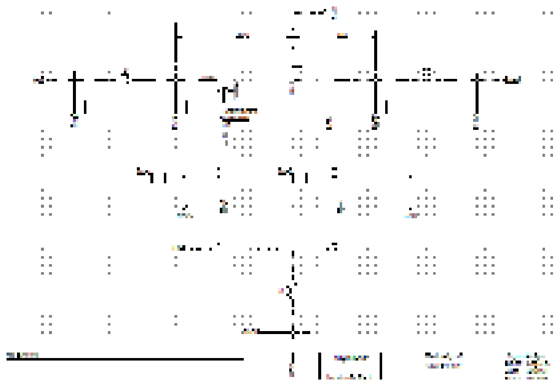

Fig 1. 9 Bus 3 Generators System

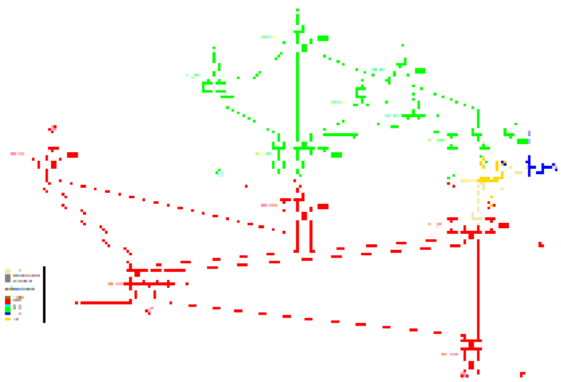

Fig 2. 14 Bus 5 Generators System

B. *Load Flow Sensitivities*

The results obtained using the Sensitivity to a Single Busbar method. The simulation is carried out in turns from the bus that is the object of research. The following are the simulation results of the load flow sensitivities for buses 4 and 9 on the 9 bus 3 generator system.

Table 1. Sensitivity values in a 9 bus 3 generator system

Line	dphi/dP (deg/MW)	dphi/dQ (deg/MVar)	dv/dP (p.u/MW)	dv/dQ (p.u/MVar)
4--5	0.031388	0.005759	0.000021	0.000258
4--6	0.031326	0.005003	0.000025	0.000308
4--7	0.031434	0.006322	0.000009	0.000116
4--8	0.031479	0.006859	0.000008	0.000107
4--9	0.031451	0.006525	0.000007	0.000087
5--4	0.031722	0.001358	0.000058	0.000260
5--6	0.039690	0.003470	0.000047	0.000216
5--7	0.067741	0.003668	0.000058	0.000286
5--8	0.062114	0.004803	0.000049	0.000217
5--9	0.053851	0.004336	0.000029	0.000104
6--4	0.031868	0.001493	0.000061	0.000306
6--5	0.040037	0.004594	0.000045	0.000212
6--7	0.046563	0.005047	0.000023	0.000118
6--8	0.053038	0.005477	0.000029	0.000161
6--9	0.061678	0.004314	0.000040	0.000209
7--4	0.031366	0.000580	0.000026	0.000116
7--5	0.066803	0.001119	0.000056	0.000284
7--6	0.045354	0.001326	0.000023	0.000119
7--8	0.086115	0.001095	0.000049	0.000292
7--9	0.071054	0.000925	0.000029	0.000110
8--4	0.031558	0.000596	0.000026	0.000108
8--5	0.061391	0.001328	0.000057	0.000215
8--6	0.051897	0.000895	0.000032	0.000163
8--7	0.086444	0.000164	0.000059	0.000293
8--9	0.089266	-0.001145	0.000059	0.000243
9--4	0.030996	0.000417	0.000005	0.000087
9--5	0.052254	0.000945	0.000018	0.000103
9--6	0.059621	0.000262	0.000010	0.000210
9--7	0.070300	0.000461	0.000012	0.000109
9--8	0.088216	-0.000032	0.000021	0.000242

Table 2. Sensitivity values of in a 14 bus 5 generator system

Line	dphi/dP (deg/MW)	dphi/dQ (deg/MVar)	dv/dP (p.u/MW)	dv/dQ (p.u/MVar)
2--3	0.025407	0	0	0
2--4	0.022509	0	-0.0000026	0
2--5	0.020508	0	-0.0000027	0
3--2	0.026171	0	0	0
3--4	0.040406	0	-0.0000049	0
3--5	0.032738	0	-0.0000017	0
4--2	0.023032	0.000349	0	0
4--3	0.040395	0.001626	0	0
4--5	0.041854	-0.003730	0.00008952	0.000244
5--2	0.020861	0.000520	0	0
5--3	0.032522	0.001493	0	0
5--4	0.041772	-0.003251	0.0000806	0.000245

C. *Critical Clearing Time In Initial Conditions*

This chapter contains the amount of cct for each bus which is the object of research. To get the CTT value, the author uses the Time Domain Simulation (TDS) method.

TABLE 3. CCT VALUE BUS 4 TO 9 SYSTEM 9 BUS 3 GENERATOR

Bus	CCT (s)
4	0.440
5	0.725
6	0.680
7	0.331
8	0.265
9	0.156

TABLE 4. CCT VALUE BUS 2 TO 5 SYSTEM 14 BUS 5 GENERATOR

Bus	CCT (s)
2	0.429
3	0.430
4	0.459
5	0.518

D. *Critical Clearing Time After Installing HVDC Lines*

After installing the HVDC line at a predetermined point, we will then look for the cct value at all installation points. The following are the simulation steps carried out to find the maximum Active Power Set point value for each HVDC line.

TABLE 5. MAXIMUM ACTIVE POWER SET POINT VALUE FOR 9 BUS 3 GENERATOR SYSTEM

Line	Power (MW)
4--5	420
4--6	200
4--7	280
4--8	160
4--9	100
5--4	180
5--6	220
5--7	350
5--8	170
5--9	110
6--4	190
6--5	240
6--7	210
6--8	230
6--9	130
7--4	140
7--5	260
7--6	170
7--8	220
7--9	110
8--4	130
8--5	210
8--6	170
8--7	350
8--9	160
9--4	140
9--5	190
9--6	190
9--7	270
9--8	350

TABLE 6. MAXIMUM ACTIVE POWER SET POINT VALUE FOR 9 BUS 3 GENERATOR SYSTEM

BUS	Daya
2--3	140
2--4	410
2--5	410
3--2	170
3--4	200
3--5	180
4--2	230
4--3	150
4--5	590
5--2	220
5--3	140
5--4	460

After knowing the maximum active power set point value for each HVDC line, a simulation is carried out to find the cct value using the TDS method.

TABLE 7. CCT VALUE IN SYSTEM 9 BUS 3 GENERATOR AFTER HDVC INSTALLATION

Line	*Critical Clearing Time* (s)					
	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9
4--5	0.841	2.168	2.139	0.396	0.301	0.170
4--6	0.467	0.717	0.678	0.325	0.264	0.163
4--7	0.879	1.204	1.865	0.396	0.304	0.172
4--8	0.266	0.830	4.298	0.286	0.224	0.160
4--9	0.000	0.275	0.331	0.231	0.329	0.159
5--4	0.286	0.138	1.374	0.168	0.189	0.145
5--6	0.586	2.228	2.398	0.373	0.292	0.171
5--7	0.906	2.068	2.627	0.440	0.312	0.170
5--8	0.470	0.851	0.623	0.354	0.280	0.164
5--9	0.496	1.117	3.628	0.478	2.138	0.168
6--4	0.555	1.150	2.706	0.344	0.266	0.151
6--5	0.744	2.084	3.208	0.427	0.294	0.156
6--7	0.820	2.078	3.198	0.440	0.302	0.160
6--8	0.795	2.120	2.946	0.440	0.316	0.171
6--9	0.277	1.052	0.854	0.358	0.549	0.168
7--4	0.000	0.000	0.000	0.000	0.000	0.000
7--5	0.422	0.889	0.995	0.342	0.271	0.155
7--6	0.444	0.841	1.793	0.343	0.278	0.163
7--8	0.389	0.662	0.497	0.336	0.274	0.161
7--9	0.218	0.098	4.548	0.227	0.110	0.165
8--4	0.198	0.718	0.618	0.238	0.213	0.157
8--5	0.533	2.208	2.694	0.387	0.283	0.149
8--6	0.489	1.051	2.580	0.359	0.280	0.156
8--7	0.835	2.108	3.238	0.617	0.324	0.151
8--9	0.876	1.548	3.692	0.350	0.502	0.171
9--4	0.120	0.478	0.768	0.310	0.252	0.131
9--5	0.489	2.218	2.666	0.326	0.244	0.133
9--6	0.431	0.777	1.858	0.303	0.241	0.137
9--7	0.671	2.148	3.278	0.417	0.266	0.131
9--8	0.600	2.238	3.308	0.416	0.279	0.137

TABLE 8. CCT VALUE IN SYSTEM 14 BUS 5 GENERATOR AFTER HDVC INSTALLATION

Line	*Critical Clearing Time* (s)			
	Bus 2	Bus 3	Bus 4	Bus 5
2--3	0.434	0.430	0.476	0.545
2--4	0.588	0.506	0.511	0.656
2--5	0.564	0.511	0.538	0.595
3--2	0.443	0.365	0.463	0.525
3--4	0.459	0.407	0.484	0.552
3--5	0.453	0.392	0.490	0.539
4--2	0.450	0.448	0.435	0.508
4--3	0.449	0.435	0.432	0.505
4--5	0.581	0.565	0.646	0.823
5--2	0.451	0.450	0.454	0.482
5--3	0.456	0.436	0.451	0.479
5--4	0.543	0.495	0.556	0.655

E. Analysis of the Relationship of Sensitivity to Changes in CCT Values

This chapter will describe the relationship between the value of sensitivity ($\partial\phi/\partial P$) and changes in cct values. The initial stage is to find the difference in the cct value of each bus after and before the HVDC channel is installed in the various possibilities. After that, we look for the average cct change in each HVDC line. Data in table 9 and 10 is sorted based on the dphi/dP value from the largest to the smallest.

TABLE 9. AVERAGE CHANGE OF CCT IN 9 BUS 3 GENERATOR SYSTEM

Line	dphi/dP (deg/MW)	Power (MW)	Average Change of cct (s)
8--9	0.08926628	160	0.757
9--8	0.08821625	350	0.730
8--7	0.08644402	350	0.779
7--8	0.08611591	220	-0.046
7--9	0.07105444	110	0.462
9--7	0.07030048	270	0.719
5--7	0.06774113	350	0.654
7--5	0.06680371	260	0.080
5--8	0.06211487	170	0.024
6--9	0.06167843	130	0.110
8--5	0.06139105	210	0.610
9--6	0.05962138	190	0.192
5--9	0.05385198	110	0.905
6--8	0.05303827	230	0.669
9--5	0.05225428	190	0.580
8--6	0.05189796	170	0.386
6--7	0.04656321	210	0.734
7--6	0.04535434	170	0.211
6--5	0.04003745	240	0.719
5--6	0.03969038	220	0.575
6--4	0.03186818	190	0.429
5--4	0.03172280	180	-0.050
8--4	0.03155852	130	-0.076
4--8	0.03147911	160	0.578
4--9	0.03145164	100	-0.212
4--7	0.03143496	280	0.371
4--5	0.03138863	420	0.570
7--4	0.03136610	140	-0.433
4--6	0.03132644	200	0.003
9--4	0.03099608	140	-0.090

Based on table 9, the line with the highest sensitivity value is line 8-9 with a value of 0.08926628 and the line with the lowest sensitivity is 9-4 with a value of 0.03099608.

The researcher also divided the data into 3 categories and took several samples from channels that had high sensitivity values, namely line 8-9, 9-8, 8-7, and 7-8 with an average cct change value of 0.555 s, middle values, namely line 5-8, 6-9, 8-5, and 9-6 had average change in cct 0.234 s, and lower from line 6-4, 5-4, 8-4, 4-8, 4-9, 4-7, 4-5, 7-4, 4-6, and 9-4 with an average change of 0.109 s.

TABLE 10. AVERAGE CHANGE OF CCT IN 14 BUS 5 GENERATOR SYSTEM

Saluran	dphi/dP (deg/MW)	Power (MW)	Average Change of cct (s)
4--5	0.04185443	590	0.195
5--4	0.04177298	460	0.103
3--4	0.04040664	200	0.017
4--3	0.04039565	150	-0.004
3--5	0.03273863	180	0.010
5--3	0.03252217	140	-0.004
3--2	0.02617191	170	-0.010
2--3	0.02540740	140	0.012
4--2	0.02303211	230	0.001
2--4	0.02250906	410	0.106
5--2	0.02086154	220	0.000
2--5	0.02050830	410	0.093

With few data it is enough to divide 2 into groups with high sensitivity values from channels 4-5 to 5-3 with an average change in cct of 0.053 s and a low sensitivity group from channels 3-2 to 2-5 with an average change in cct 0.034.

IV. CONCLUSION

Based on the analysis of the two systems, it shows that the channel with a large sensitivity value will give a higher change in cct value compared to the other with a lower value when paired with an HVDC line.

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