

5.2 DC link Model

The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

The control of power in a DC link can be achieved through the control of current or voltage. From minimization of loss considerations, we need to maintain constant voltage in the link and adjust the current to meet the required power.

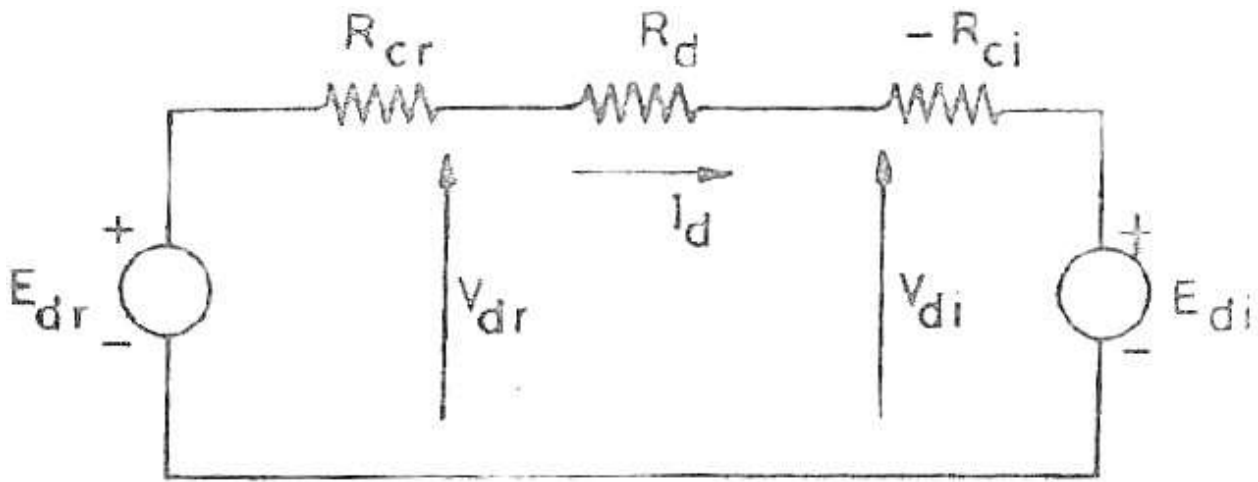


Figure 5.2.1 Steady state equivalent circuit of a 2 terminal DC link

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-84]

Consider the steady state equivalent circuit of a two terminal DC link. This is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angles. Also the number of series connected bridges (n_b) in both stations (rectifier and inverter) are the same.

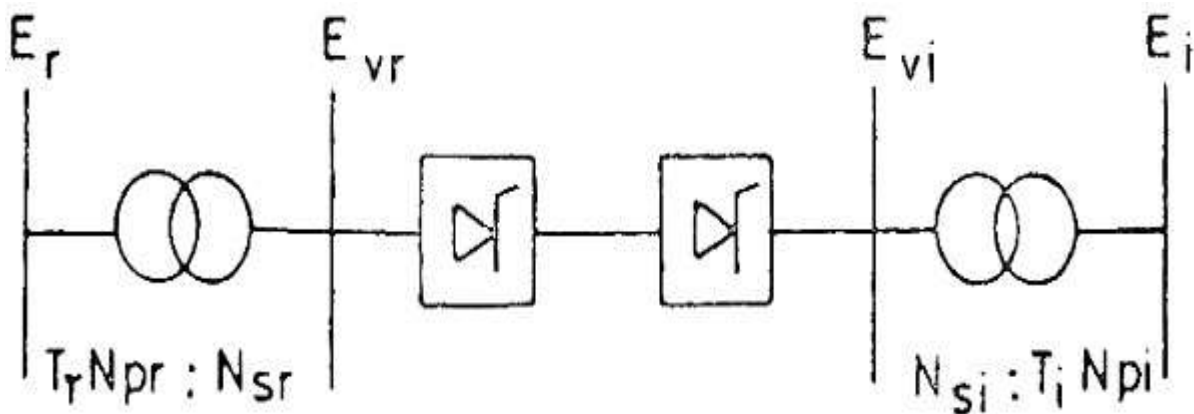


Figure 5.2.2 Schematic of DC link showing transformer ratios

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-84]

The voltage sources E_{dr} and E_{di} are defined by

$$E_{dr} = (3\sqrt{2}/\pi) n_b E_{vr} \cos\alpha_r \text{----- (1)}$$

$$E_{di} = (3\sqrt{2}/\pi) n_b E_{vi} \cos\gamma_i \text{----- (2)}$$

where E_{vr} and E_{vi} are the line to line voltages in the valve side windings of the rectifier and inverter transformer respectively. From the above figure these voltages can be obtained by

$$E_{vr} = \frac{N_{sr} E_r}{N_{pr} T_r}, \quad E_{vi} = \frac{N_{si} E_i}{N_{pi} T_i} \text{---- (3)}$$

where E_r and E_i are the AC (line to line) voltages of the converter buses on the rectifier and inverter side. T_r and T_i are the OFF-nominal tap ratios on the rectifier and inverter side.

Combining equations (1), (2) and (3),

$$E_{dr} = (A_r E_r / T_r) \cos\alpha_r \text{----- (4)}$$

$$E_{di} = (A_i E_i / T_i) \cos\gamma_i \text{----- (5)}$$

where A_r and A_i are constants.

The steady-state current I_d in the DC link is obtained as

$$I_d = \frac{(E_{dr} - E_{di})}{R_{cr} + R_d - R_{ci}}$$

Substituting equations (4) and (5) in the above equation, we get

$$I_d = \frac{(A_r E_r / T_r) \cos\alpha_r - (A_i E_i / T_i) \cos\gamma_i}{R_{cr} + R_d - R_{ci}}$$

The control variables in the above equation are T_r , T_i and α_r , β_i . However, for maintaining safe commutation margin, it is convenient to consider γ_i as control variable instead of β_i .

As the denominator in the final equation is small, even small changes in the voltage magnitude E_r or E_i can result in large changes in the DC current, the control variables are held constant. As the voltage changes can be sudden, it is obvious that manual control of converter angles is not feasible. Hence, direct and fast control of current by varying α_r or γ_i in response to a feedback signal is essential.

While there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at Constant Extinction

Angle (CEA) which is slightly above the absolute minimum required for the commutation margin. This results in reduced costs of the inverter stations, reduced converter losses and reactive power consumption. However, the main drawback of CEA control is the negative resistance characteristics of the converter which makes it difficult to operate stably when the AC system is weak (low short-circuit ratios). Constant DC Voltage (CDCV) control or Constant AC Voltage (CACV) control are the alternatives that could be used at the inverter.

Under normal conditions, the rectifier operates at Constant Current (CC) control and the inverter at the CEA control.

The power reversal in the link can take place by the reversal of the DC voltage. This is done by increasing the delay angle at the station initially operating as a rectifier, while reducing the delay angle at the station initially operating as the inverter. Thus, it is necessary to provide both CEA and CC controllers at both terminals.

The feedback control of power in a DC link is not desirable because

- 1) At low DC voltages, the current required is excessive to maintain the required level of power. This can be counterproductive because of the excessive requirements of the reactive power, which depresses voltage further.
- 2) The constant power characteristic contributes to negative damping and degrades dynamic stability.

5.5 IEEE 14-Busbar system

The test systems are based on the Institute of Electrical and Electronics Engineers' (IEEE) 14- bus system case studies for power system networks. The system base MVA and the base voltage are 100 MVA and 100 KV, respectively. The tolerance for convergence checking is 0.00001, the details of which are provided here Case I: The AC line between bus bars 4 and 5 is replaced by two DC links. Case II: The AC lines between bus bars 2-4, 2-5, and 4-5 are replaced by a DC link; a three-terminal DC link is obtained between bus bars 2, 4 and 5.

Table 1: Load Flow solution of 14 Bus system for mode 1 with two converters

I- Voltage magnitude, angle, active, and reactive powers

Load Flow solution				
Bus	V	Ang	P(pu)	Q(pu)
1	1.0600	0.0000	0.0000	0.0000
2	1.0450	-9.7872	0.2724	0.1803
3	1.0100	-20.8167	0.9901	0.2567
4	0.9791	-20.9028	0.5057	0.0850
5	0.9800	-18.9441	0.1381	0.0571
6	1.0700	-24.8154	0.2048	0.1190
7	1.0374	-23.8475	0.0520	0.0305
8	1.0900	-23.8475	0.0360	0.0421
9	1.0311	-25.4315	0.3591	0.2635
10	1.0224	-25.6149	0.1422	0.1001
11	1.0436	-25.3287	0.0810	0.0662
12	1.0556	-25.7292	0.1068	0.0423
13	1.0477	-25.7671	0.2169	0.1272
14	1.0142	-26.6614	0.1902	0.0910

II- Results of the DC converters output

Converters No.	Variables				
	V_d	I_d	T	$\cos\theta$	Φ
1	0.941	0.101	1.000	0.854	19.372
2	0.926	0.136	1.000	0.998	24.356

Table 2: Load Flow solution of 14-Bus system for mode 2 with two converters

I- Voltage magnitude, angle, active, and reactive powers

Load flow Solution				
Bus	V	Ang	P(pu)	Q(pu)
1	1.0600	0.0000	0.0000	0.0000
2	1.0450	-9.7872	0.2993	0.1583
3	1.0100	-20.8167	1.1140	0.2797
4	0.9889	-20.9028	0.4912	0.0496
5	0.9926	-18.9441	0.1097	0.0321
6	1.0700	-24.8154	0.1912	0.1096
7	1.0420	-23.8475	0.0130	0.0171
8	1.0900	-23.8475	0.0082	0.0230
9	1.0284	-25.4315	0.3054	0.2187
10	1.0260	-25.6149	0.1637	0.0985
11	1.0455	-25.3287	0.0497	0.0457
12	1.0559	-25.7292	0.1278	0.0350
13	1.0483	-25.7671	0.2045	0.0814
14	1.0169	-26.6614	0.2138	0.0682

Results of the DC converters output

Converters No.	Variables				
	V_d	I_d	T	$\cos\theta$	Φ
1	0.865	0.097	0.812	0.882	46.466
2	1.070	-0.642	1.500	0.771	21.159

For 14 bus systems with two converters we concluded that the overall active power is improved after using the converters as well as the overall reactive power for mode 1. For mode 2 to mode 7 the active and reactive power is improved for some buses but became worse for others. For example the active power at bus 4 without using the converters was 47.8 MW and became 50.57 MW after using the converters for mode 1 but it is changed to be 49.12 MW for mode 2, 53.14 MW for mode 3, 60.15 MW for mode 4, 55.50 MW for mode 5, 52.10 MW for mode 6, and 56.21 MW for mode 7. Also the reactive power at bus 4 without using the converters was 3.9 MVAR and became 8.50 MVAR for mode 1 but it is changed to be 4.96 MVAR for mode 2, 10.72 MVAR for mode 3, 4.21 MVAR for mode 4, 12.03 MVAR for mode 5, 6.01 MVAR for mode 6, 11.00 MVAR for mode 7. For bus 12 without using the converters was 6.1 MW and became 10.68 MW after using the converters for mode 1 but it is changed to be 12.78 MW for mode 2, 8.40 MW for

mode 3, 7.75MW for mode 4, 17.73MW for mode 5, 15.10MW for mode 6, and 9.78MW for mode 7. Also the reactive power at bus 12 without using the converters was 1.6 MVAR and became 4.23 MVAR for mode 1 but it is changed to be 3.50 MVAR for mode 2 , 7.73 MVAR for mode 3, 4.90 MVAR for mode 4, 2.87 MVAR for mode 5, 3.61 MVAR for mode 6, 3.35 MVAR for mode 7.

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5.4 IEEE 30-Busbar system

The standard bus system has been modified into two and three -terminal DC link systems in order to solve the AC, DC and HVDC systems independently. In terms of accuracy and computational speed, this enhanced method is superior to any conventional Newton-Raphson (NR) load flow and performs effectively under various types of network conditions where other methods cannot give satisfactory results. Simulation studies have also been conducted under different control specifications. It is not possible to compare results of various research papers because each one uses a different test system.

The test systems are based on the Institute of Electrical and Electronics Engineers' (IEEE) 30-bus system case studies for power system networks. The system base MVA and the base voltage are 100 MVA and 100 KV, respectively. The tolerance for convergence checking is 0.00001, the details of which are provided here: Case I: AC line between bus bars 2 and 5 is replaced by two DC links. Case II: A three-terminal DC link is formed between bus bars 2 and 7 by placing an AC line connecting bus bars 2 and 5 by a two-terminal DC link and introducing a two-terminal DC link between bus bars 2 and 7 and bus bars 5 and 7.

Test Results

The test results of the method are compared with those corresponding to the Newton-Raphson power flow method. A number of sample systems are studied through the proposed method and its HVDC power flow performance. In order to investigate the feasibility of the proposed technique, a large number of power systems of varying sizes have been modified under different system conditions in two- and three-terminal DC link configurations in order to solve HVDC power flow problems.

Table 15: Load Flow solution of 30-Bus system for mode 1 with two converters

I- Voltage magnitude, angle, active, and reactive powers

Load Flow Solution				
Bus	V	Ang	P(pu)	Q(pu)
1	1.0600	0.0000	0.0000	0.0000
2	1.0430	-10.1663	0.3190	0.1678
3	1.0267	-16.3740	0.0512	0.0459
4	1.0135	-20.3370	0.1031	0.0713
5	1.0100	-22.1488	0.9864	0.2412
6	1.0263	-23.1617	0.0492	0.0540
7	1.0112	-23.2977	0.2803	0.2074
8	1.0100	-23.6508	0.3901	0.3881
9	1.0517	-26.1008	0.0125	0.0480
10	1.0341	-27.6901	0.1118	0.0369
11	1.0820	-26.1008	0.0271	0.0095
12	1.0595	-26.7267	0.1153	0.1521
13	1.0710	-26.7267	0.0217	0.0083
14	1.0424	-27.7283	0.0978	0.0426
15	1.0458	-27.8073	0.1256	0.0713
16	1.0412	-27.4283	0.0488	0.0572
17	1.0307	-27.8331	0.1520	0.1087
18	1.0229	-28.5075	0.0398	0.1300
19	1.0183	-28.7170	0.1101	0.0836
20	1.0215	-28.5230	0.0375	0.0911
21	1.0205	-28.2056	0.1832	0.2168
22	1.0450	-28.0025	0.0207	0.0122
23	1.0208	-28.2020	0.0635	0.0590
24	1.0727	-28.3195	0.1282	0.0973
25	1.0192	-28.1403	0.0116	0.0325
26	1.0016	-28.5671	0.0813	0.0697
27	1.0918	-27.7459	0.0420	0.0153
28	1.0215	-23.7767	0.0519	0.0448
29	1.0125	-29.0094	0.0452	0.1007
30	1.0014	-29.8888	0.2074	0.0309

II- Results of the DC converters output

Converters No.	Variables				
	V_d	I_d	T	$\cos\theta$	Φ
1	1.287	0.098	0.993	0.961	12.510
2	0.942	-0.464	1.010	0.844	23.856

5.1 Per unit system

In the power systems analysis field of electrical engineering, a per-unit system is the expression of system quantities as fractions of a defined base unit quantity. Calculations are simplified because quantities expressed as per-unit do not change when they are referred from one side of a transformer to the other. This can be a pronounced advantage in power system analysis where large numbers of transformers may be encountered. Moreover, similar types of apparatus will have the impedances lying within a narrow numerical range when expressed as a per-unit fraction of the equipment rating, even if the unit size varies widely. Conversion of per-unit quantities to volts, ohms, or amperes requires a knowledge of the base that the per-unit quantities were referenced to. The per-unit system is used in power flow, short circuit evaluation, motor starting studies etc.

The main idea of a per unit system is to absorb large differences in absolute values into base relationships. Thus, representations of elements in the system with per unit values become more uniform.

A per-unit system provides units for power, voltage, current, impedance, and admittance. With the exception of impedance and admittance, any two units are independent and can be selected as base values; power and voltage are typically chosen. All quantities are specified as multiples of selected base values. For example, the base power might be the rated power of a transformer, or perhaps an arbitrarily selected power which makes power quantities in the system more convenient. The base voltage might be the nominal voltage of a bus. Different types of quantities are labeled with the same symbol (pu); it should be clear whether the quantity is a voltage, current, or other unit of measurement.

1. A common three-phase voltampere base is used throughout the system, where

$$S_{base,3\Phi} = 3S_{base,1\Phi} .$$

2. Once selected at a point in the network, the three-phase voltage base must vary according to the line-to-line transformer turns ratios.

Convenient formulas relating single-phase to three-phase bases are given below.

$$S_{base,1\Phi} = V_{base,line - neutral} * I_{base} ,$$

$$S_{base,3\Phi} = 3S_{base1\Phi}$$

$$Z_{base} = \frac{V_{2base}^2}{S_{base 3\Phi}}$$

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5.3 Power Flow Analysis

Newton-Raphson Solution Algorithm

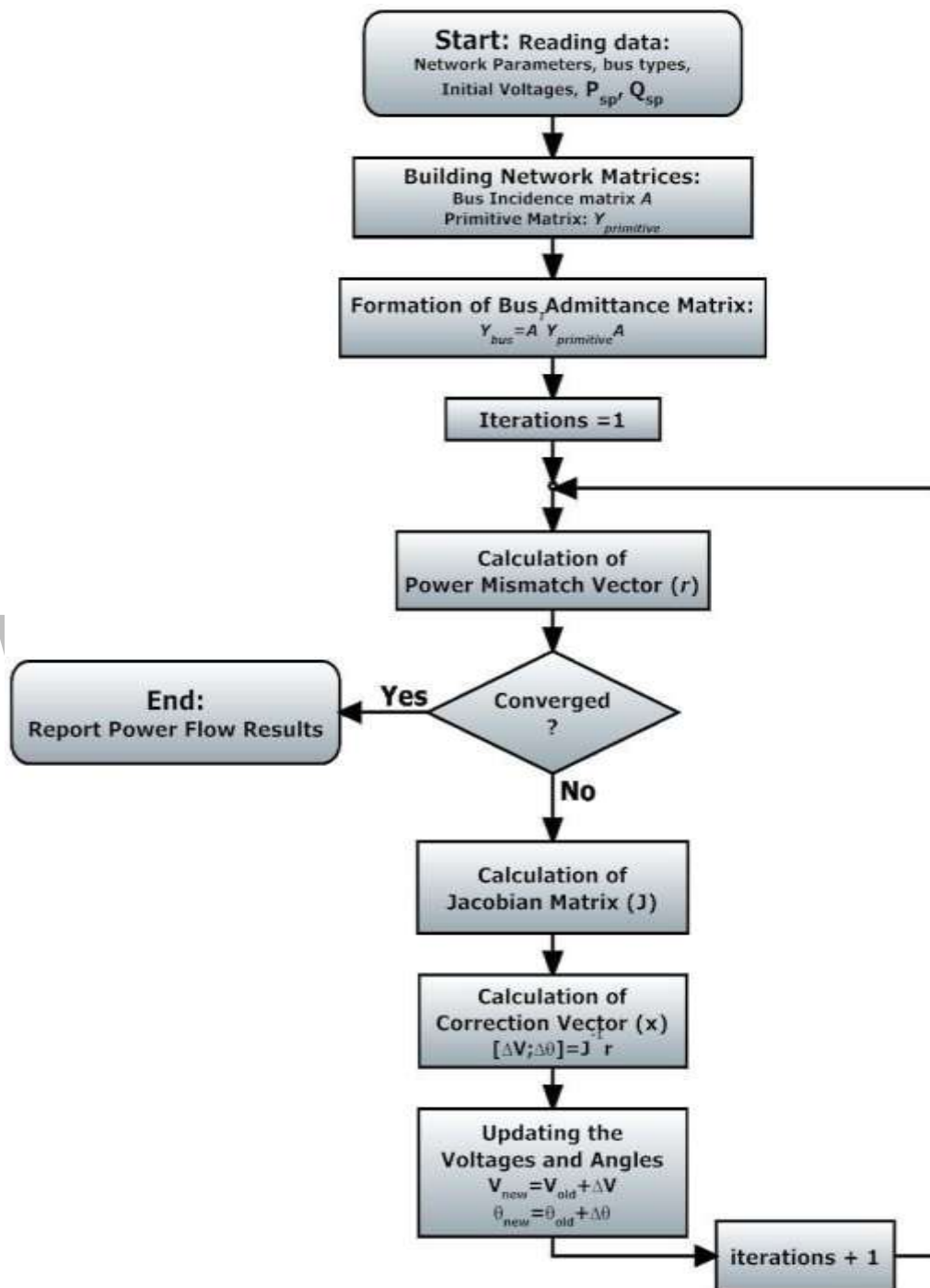


Figure 5.3.1 Newton Rapson Solution flow chart

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-84]

HVDC Load Flow Solution Method

High Voltage Direct Current (HVDC) transmission is important for long distance, underground, and submarine transmission. Due to the increasing strains on existing systems, it is necessary to develop a better method for performing the load flow analysis of an integrated HVDC power system. However, the power flow has to be substantially enhanced to be capable of modeling the operating state of the combined AC and DC systems, and this must be done fast and efficiently under the specified conditions of load generation and DC system control strategies. The development of an enhanced HVDC-load flow system based on the Newton - Raphson method is the focus of this chapter. The variation of the DC link chosen for the problem formulation are: (1) the converter, terminal DC voltage; (2) the real and imaginary components of the transformer secondary current; (3) converting transformer tap ratios; (4) the firing angle of the rectifier; and (5) the current in the DC link. The equations relating these five variables and their solution strategy are discussed. As the model developed is independent of a particular control mode of the DC link, the AC and DC link equations are solved separately and thus the integration into a standard load flow program is possible without significant modifications of the AC load flow algorithm. In the AC system iterations, each converter is designed as a complex power load at the AC terminal bus bar, and the DC link equations are solved using the most recent value of the AC bus bar voltage. The AC and DC system equations are solved simultaneously