A Modified Approach for Load Flow Analysis of Integrated AC-DC Power Systems

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Abstract
High Voltage Direct Current (HVDC) power distribution systems have been extensively used in modern transmission system. The major concern of the HVDC transmission is the loadflow in the system. This paper is dealing with the development of loadflow solution for a HVDC link in a power system. The loadflow solution is based on the Fast Decoupled Method which needs some iteration to obtain the result. The paper exposed us to the integration of HVDC link with an AC power system. Variables of the direct current link which have been chosen for simulation are the converter terminal DC voltages, converter transformer tap ratios, firing angle of the rectifier and current in the HVDC link. An algorithm has been developed to solve the HVDC link power system loadflow and the algorithm has been tested on the IEEE test system.

Keyword
HVDC, loadflow, fast decoupled method

I. INTRODUCTION

Load Flow is power system parlance for the steady-state solution of a network. This does not essentially differ from the solution of any other type of network except that certain constraints are peculiar to power supply. The following combinations of quantities are usually specified at the system busbars for load-flow studies.
Load-flow studies are performed to investigate the Flow of MW and MVAr in the branches of the network, busbar voltages. Optimum system loses rating and tap range of transformer. However the more important parameter in loadflow study are Voltage (magnitude and angle), real power and reactive power at each buses.

DC transmission became practical when long distances were to be covered or where cables were required. The increase in need for electricity after the Second World War stimulated research, particularly in Sweden and in Russia. In 1950, a 116 km experimental transmission line was commissioned from Moscow to Kasira at 200 kV[1]. The first commercial HVDC line built in 1954 was a 98 km submarine cable with ground return between the island of Gotland and the Swedish mainland [1]. Thyristors were applied to DC. Transmission in the late 1960's and solid-state valves became a reality. In 1969, a contract for the Eel River DC. Link in Canada was awarded as the first application of sold state valves for HVDC transmission [1]. Today, the highest functional DC voltage for DC transmission is 600 kV for the 785 km transmission line of the Itaipu scheme in Brazil. DC link is now an integral part of the delivery of electricity in many countries throughout the world because:

1. An overhead DC transmission line with its towers can be designed to be less costly per unit of length than an equivalent AC line designed to transmit the same level of electric power. However the DC converter stations at each end are more costly than the terminating stations of an AC. line and so there is a breakeven distance above which the total cost of DC transmission is less than its AC transmission alternative.

2. If transmission is by submarine or underground cable, the breakeven distance is much less than overhead transmission. It is not practical to consider AC cable systems exceeding 50 km.

3. Some AC electric power systems are not synchronized to neighboring networks It is physically impossible to connect the two together by direct AC methods in order to exchange electric power between them. However, if a DC converter station is located in each system with an interconnecting DC link between them, it is possible to transfer the required power flow even though the AC systems so connected remain asynchronous.

4. One of the fundamental advantages with HVDC is that it is very easy to control the active power in the link. Depending on the application and the network requirements, the control system can include a number of functions.

The common perception that losses of HVDC are lower is not correct. The level of losses is designed into a transmission system and is regulated by the size of conductor selected.

The structure of a HVDC converter substation is shown in Figure 1.

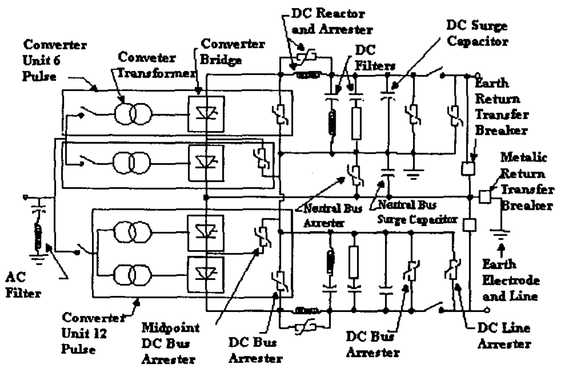

Figure 1 Example of a HVDC substation

II. LOADFLOW SOLUTION BY FAST DECOUPLED METHOD

In loadflow solution for a large power system, iteration methods are normally used to solve the problem. The normally used method are the Gauss-Siedel Method, Newton-Raphson Method and Fast Decoupled Method.

For power systems there are always 3 types of buses such as slack or floating bus, voltage-controlled bus and load bus. For slack or floating bus: one node is always specified by a voltage constant in magnitude and phase. The effective generator at this node supplies the losses to the network: this is necessary because the magnitude of the losses will not be known until the calculation of currents is complete and this cannot be achieved unless one busbar has no power constraint and can feed the required losses into the system. The location of the slack node can influence the complexity of the calculations: the node approaching most closely an infinite busbar should be used.

The Fast Decoupled Method is probably the most commonly method used for load flow solution because it is computationally the fastest, and for most power systems, it is very reliable. The FDM however does have convergence difficulties on systems with branches that have large resistance to reactance ratios. The Fast Decoupled method utilizes some justifiable network assumption, apart from P, θ, Q, V decoupling such as ($G_{km} \sin \theta_{km} << B_{km}$ G_{km} + jB_{km} represent the *km*th element of the Y-bus) and the final FDM load flow equation are [5] :

$$\left[\frac{\Delta P}{V}\right] = [B'][\Delta\theta] \quad (1)$$

$$\left[\frac{\Delta Q}{V}\right] = [B''][\Delta V] \quad (2)$$

where

$$B'_{km} = -\frac{1}{X_{km}}(m \neq k) \quad (3)$$

$$B'_{kk} = \sum_{m \neq k} \frac{1}{X_{km}} \quad (4)$$

$$B''_{km} = -B_{km}(m \neq k) \quad (5)$$

$$B''_{kk} = \sum_{m \neq k} B_{km} \quad (6)$$

Matrices B' and B" are real and constant in value

For each bus in a power network the power injection equations can be written as:

$$\frac{Pi}{Vi} = V_i G_{ij} + \sum_{i \neq j} V_j \left[G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right] \quad (7)$$

$$\frac{Q_i}{Vi} = -V_i B_{ij} + \sum_{i \neq j} V_j \left[G_{ij}\sin(\theta_i - \theta_j) + B_{ij}\cos(\theta_i - \theta_j)\right] \quad (8)$$

The FDM to solve the load flow problem is basically the Newton's method where the P - θ is decoupled. The assumption Gij << Bij allows the decoupling. The assumption V1 = 1 and cos (θi - θj) = 1 and sin (θi - θj) = 0 produce the following constant Jacobian terms

$$\frac{\partial P_i}{\partial \theta_j} = -B_{ij} \quad (9)$$

$$\frac{\partial P_i}{\partial \theta_i} = \sum_j B_{ij} \quad (10)$$

$$\frac{\partial Q_i}{\partial V_j} = -B_{ij} \quad (11)$$

$$\frac{\partial Q_i}{\partial V_i} = -B_{ii} \quad (12)$$

and

$$B'_{ij} = -B_{ij} \quad (13)$$

$$B'_{ii} = \sum_j B_{ij} \quad (14)$$

$$B''_{ij} = -B_{ij} \quad (15)$$

$$B''_{ii} = -B_{ii} \quad (16)$$

Are the matrices to be used in the FDM. FDM uses the approximation

$$B'_{ij} = \frac{1}{X_{ij}} = -B_{ij} - \frac{G_{ij}^2}{B_{ij}} \quad (17)$$

$$B'_{ii} = -\sum_j B'_{ij} \quad (18)$$

The simple algorithm of the Fast Decoupled Method can be illustrated as below:

1. Initialized $v \leftarrow 0$
2. Compute angle corrections
   $\Delta\theta^v = [B']^{-1} \Delta P (V^v, \theta^v)$
   Update angle vector
   $\theta^v \leftarrow \theta^v + \Delta\theta^v$
3. Compute voltage magnitudes
   $\Delta V^v = [B'']^{-1} \Delta P (V^v, \theta^v)$
   Update angle vector
   $V^v \leftarrow V^v + \Delta V^v$
   Update $V \leftarrow V+1$, and go to step 2 until convergence ($\Delta\theta$ and $\Delta V \cong 0$)

III. INTEGRATION OF THE DC LINK EQUATIONS.WITH AC LOADFLOW

The sequential approach for integration of the HVDC link equations in an AC load flow program has been followed. In this approach, the AC and DC link equations are solved separately and thus the integration into standard load-flow program is carried out without significant modifications of the AC loadflow algorithm. For the AC system iterations, each converter is simply modeled as a complex power load at the AC terminal busbar. The DC link equations are solved using the latest updated value of the AC bus bar voltage.

IV. MODEL THE DC LINK IN A POWER SYSTEM

Figure 2 shows the schematic diagram of the basic model of the DC link interconnecting busbars (r) and (i). [2]

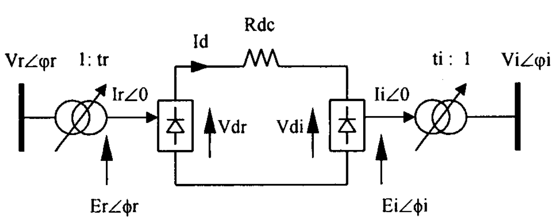

Figure 2 Schematic diagram of DC link

The following variables are involved in the representation, and need to be discussed:

1. V -converter terminal bus bar nodal voltage with phase angle referred to converter reference.
2. $E \angle \phi$ -alternating voltage at the converter transformer secondary.
3. $I \angle 0$ -alternating current at the converter transformer secondary.
4. γ,β -firing & extinction angle respectively.
5. t -transformer tap ratio.
6. Vd, Id -direct voltage and current at the link

In the results of the load flow, we would usually be interested in the AC busbar voltages and the converter end DC voltages. Thus E may be treated as an intermediate variable and eliminated from the equations. Similarly, we are more interested in the DC link current than the converter transformer secondary current. Hence $i\angle 0^0$ may also be eliminated from the equations. In the sequential approach, since we model the converters as constant loads on the AC. system,ϕ need not be used as a variable.

The value of V is available as the latest updated AC voltage at the converter bus bar. We are now left with Vdr, Vdi, tr , ti, d and Id. We have four equations relating, these seven variables. [2] They are:

$$Vd_r = Vd_i + Rdc\, I_d \quad (19)$$

$$Pd_r = Vd_r I_d \text{ or } Pd_i = Vd_i\, Id \quad (20)$$

$$Vd_r = K1\, t_r V_r \cos\gamma - 3/\pi\, Id\, X \quad (21)$$

$$Vd_i = K1\, t_i V_i \cos\beta - 3/\pi\, IdX_i \quad (22)$$

Either the rectifier end power (Pd_r) or the inverter end power (Pd_i) is usually specified as data. Also the inverters bus voltage and the minimum values of α and δ are also specified as data.

Now all the DC link variables are obtained and the modeling of the link is complete.

V. ALGORITHM OF AC-DC LOADFLOW

Equations for modeling the DC link have been derived and we are to see how these equations are to be integrated with an AC load flow program. A flowchart of the same is given in Figure 3.

If Pdr is specified, then knowing Vdr, Id is calculated from equation (20). Then equation (1) is used to obtain the value of Vdr. If, on the other hand, Pdr is specified, then equation (19) and (20) are solved simultaneously to get the values of Id and Vdr. To keep the reactive power consumption of the converters minimum, it is necessary to keep the values of α and δ as close to their minimum value as possible. Hence we set $\gamma = \gamma min$ and $\beta=\beta min$. Using the latest updated value of Vi and Vr in equations (21) and (22).

Having solved for the DC variables, we now calculate the real and reactive power at each converter. The complex power expression at converter 'c' is [2]

$$S(c) = Vd(c)\, Id + j\, Vd(c)\, Id \tan \phi(c) \quad (23)$$

where,

$\tan \phi(c) = \text{sgn}(c)\, 2x+\text{Sin}2\theta(k)-\sin(\theta(c)+x)\, /$

$$\cos 2\theta(c) - \text{Cos}\, 2(\theta(c) +x) \quad (24)$$

$$\text{and } x = \cos^{-1} [\, 2Vd(c)/Vo(c) - \cos \theta(c)] - \theta(c) \quad (25)$$

where, $Vo(c) = 3\sqrt{2}/\pi\, V(c)$

where V(c) is the alternating phase-phase voltage at the converter terminals.

In the above expression,

If converter (c) is the rectifier, then $\theta(c) = \gamma$ and $\text{sgn}(c) = 1$.
If converter (c) is the inverter, then $\theta(c) = \beta$ and $\text{sgn}(c) = -1$.

One iteration of the .AC. load flow is carried out assuming constant complex power loads at the converter bus bars, given by the above expression This gives new values of Vr and Vi and these are used in equations (21) and (22) to get new values of tr and ti and hence new values of complex power. The above procedure is repeated until the AC load flow converges.

VI. APPLICATION OF THE ALGORITHM TO A HVDC LINK POWER SYSTEM

The test system is a IEEE 9 bus bars system. The line connecting busbar 4 and 5 of the system is replaced by a DC link characteristics of which given in Table 2. Reactive power loads of generator buses have not been considered, but this can be easily included if desired. The rest of the system is the same as the 9-bus system. The diagram for the system is given in Figure 4 and the line data is given in Table 1.

The result of the AC simulation is given in Table 3 and the DC link result is given in Table 4. The algorithm is tested on another IEEE 11 busbars power system as shown in Figure 5. The line data of the system is given in Table 5. The line connecting busbar 5 and 6 are replace by a dc link with the characteristic as given in Table 6.

The result of AC. simulation is given in Table 7 and the DC link result is given in Table 8.

VII. DISCUSSION AND RESULT

The design of a HVDC link converter substation is ver dependent upon the characteristic of the DC link such as the commutation reactance. In modern converter station, the range of the commutation reactance is from 0.1 to 0.15 per unit. From the simulation the AC. result is independent from the DC result but the DC result is gained from the AC value. For the AC. system result, the voltage for each bus is a almost equal to 1 because the estimated value or ideal value for load buses are 1. If the voltage value is far-exceeded 1, it means that overload condition is happening in the bus.

VIII. CONCLUSION

An approach of carrying out the loadflow analysis for a HVDC link power system has been presented. The fast-decoupled method has been used as it has high accuracy and short execution time. A simplified model of DC link integrated with an AC loadflow has been developing with the minimum amount of modification. The simulation on a 9 bus system is illustrated with its result. The simulations give us the information of the maximum load that each bus can handle with the certain amount of power generated.

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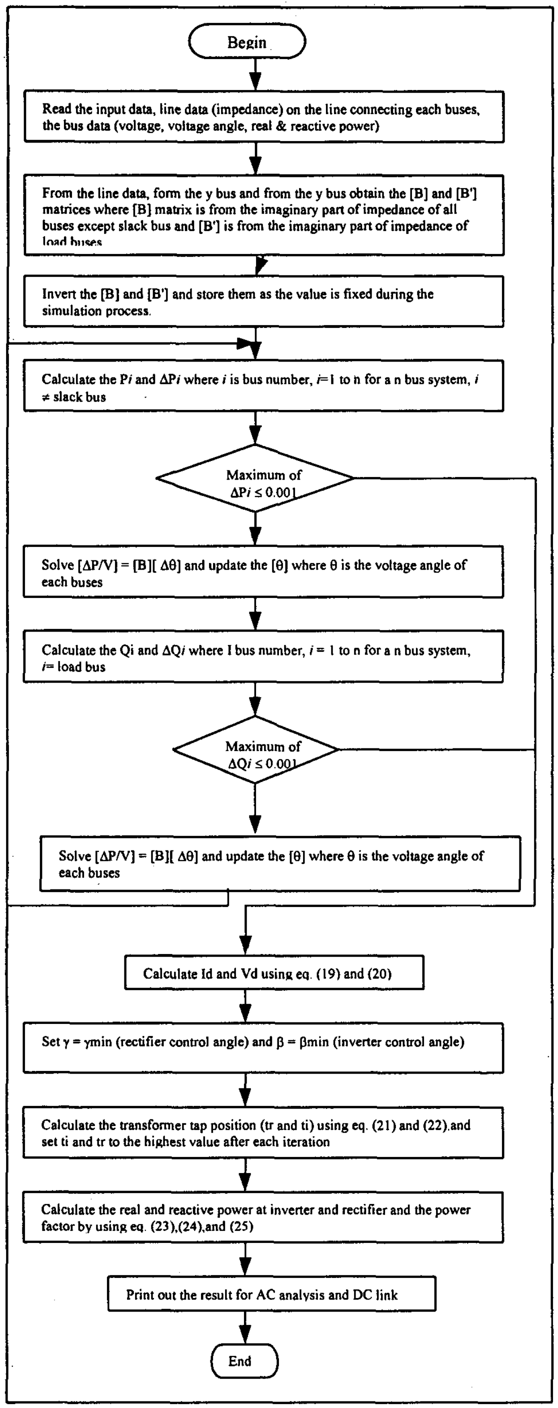

Figure 3 Flow Chart of the Algorithm

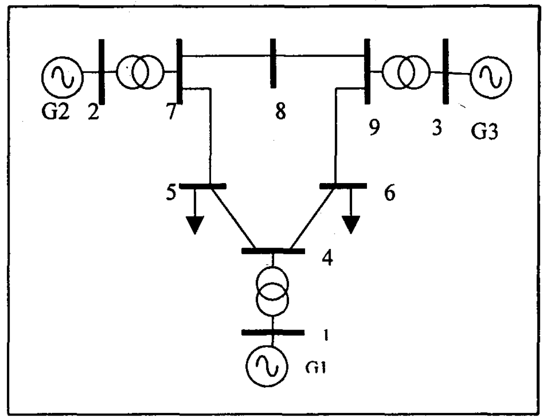

Figure 4 One-line diagram for 9 buses system [DC link 5 (rectifier)-4(inverter)]

Table 1 Line data of 9 busbars power system

Line	Busbar	R (p.u)	X (p.u)	B/2 (p.u)
1	1-4	0.0000	0.0576	0.0000
2	4-5	0.0100	0.0850	0.0880
3	4-6	0.0170	0.0920	0.0790
4	5-7	0.0320	0.1610	0.1530
5	6-9	0.0390	0.1700	0.1790
6	2-7	0.0000	0.0635	0.0000
7	7-8	0.0085	0.0720	0.0745
8	8-9	0.0119	0.1008	0.1045
9	3-9	0.0000	0.0586	0.0000

Table 2 DC link characteristic

	Rectifier	Inverter
Bus Number	5	4
Commutation reactance	0.126	0.07275
Minimum control angle	7	10
Transformer regulation range	± 15%	± 15%
Number of tap positions	27	19
Filter admittance	0.4902	0.6301
Resistance of the DC line	0.00334	
DC power flow setting	0.5857	
Inverter end DC voltage	1.284	

(All in p.u 100 MVA base. Voltage base 100kV)

Table 3 AC loadflow result

Bus No	Voltage	Angle	Real Power	Reactive power
1	1.0400	0.0000	0.7192	0.1445
2	1.0251	12.358	1.6300	-0.4213
3	1.0250	5.801	0.8500	0.0983
4	1.0242	-1.600	0	0
5	0.9927	-2.569	-1.250	-0.500
6	1.0111	-2.899	-0.900	-0.300
7	1.0264	-6.693	0	0
8	1.0190	-4.371	-0.500	-0.350
9	1.0320	-3.099	-0.300	0

Table 4 DC link result

	Rectifier	Inverter
Dc voltage	1.285	1.284
Transformer tap position	0.974	0.971
Control angles	8.137	11.680
Real power flow	0.586	0.586
Reactive power flow	0.123	0.221
Power factor	0.935	0.978
Current in DC link	0.456	

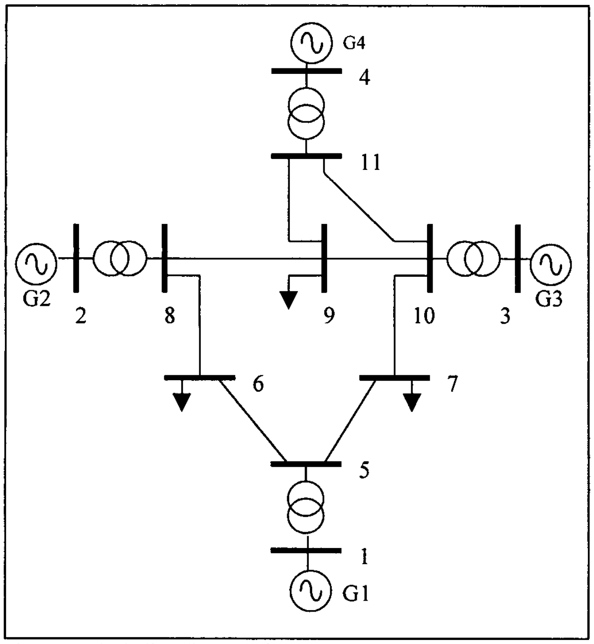

Figure 5 Single line diagram of 11 busbars power system [DC link 5 (rectifier) - 6 (inverter)

Table 5 Line data of 11 busbars power system

Line	Busbar	R (p.u)	X (p.u)	B/2 (p.u)
1	1-5	0.0000	0.0576	0.0000
2	5-6	0.0100	0.0850	0.0880
3	5-7	0.0170	0.0920	0.0790
4	6-8	0.0320	0.1610	0.1530
5	7-10	0.0390	0.1700	0.1790
6	2-8	0.0000	0.0635	0.0000
7	8-9	0.0085	0.0720	0.0745
8	9-10	0.0119	0.1008	0.1045
9	3-10	0.0000	0.0586	0.0000
10	9-11	0.0119	0.1008	0.0251
11	4-11	0.0000	0.0600	0.0000
12	10-11	0.0000	0.0586	0.0251

Table 6 DC link characteristic

	Rectifier	Inverter
Bus number	5	6
Commutation reactance	0.1126	0.07275
Minimum control angle	8	10
Transformer regulation range	± 15%	± 15%
Number of tap positions	20	15
Filter admittance	0.4526	0.6012
Resistance of the DC line	0.00334	
DC power flow setting	0.5857	
Inverter end DC voltage	1.284	

(All in p.u 100 MVA base. Voltage base 100kV)

Table 7 AC loadflow result

Bus No	Voltage	Angle	Real power	Reactive power
1	1.0400	0.0000	0.7192	0.3457
2	1.0251	6.831	1.6300	0.1928
3	1.0250	1.523	0.8500	-3.2216
4	1.0034	-0.832	0.0000	-0.2646
5	1.0264	-4.036	-1.2500	-0.5000
6	0.9921	-4.589	-0.9000	-0.3000
7	1.0402	-3.126	0.0000	0.0000
8	1.0182	1.232	-0.5000	-0.3500
9	1.0253	-0.618	-0.3000	0.0000
10	1.0280	-1.186	-0.8000	-0.2000
11	1.0159	-0.832	0.0000	0.0000

Table 8 DC link result

	Rectifier	Inverter
DC voltage	1.285	1.284
Transformer tap position	0.961	0.971
Control angles	8.349	11.493
Real power flow	0.586	0.586
Reactive power flow	0.101	0.224
Power factor	0.934	0.985
Current in DC link	0.456	