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Analysis of AC-DC Load Flow using G-S Approach

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Abstract

This study offers an approach for determining power flow in an AC system with HVDC link. For AC/DC systems, an unadorned and sound approach for sequential method with modified Gauss Seidel load flow is devised. The conventional technique for solving AC-DC load flow is a simultaneous technique in which the computation burden exists. This leads to the power flow analysis using sequential technique. This technique is based on the implementation of node infusion concept to every bus. The Direct Current system is influenced by the power injected into the buses to which it is linked. The constraints of both the systems are linked by iterations between Alternating Current and Direct Current load flow algorithms. With each iteration of the algorithm of this technique, the connection between the Alternating Current and Direct Current equations of the real and reactive powers at the rectifier buses and also the Alternating Current voltages at the rectifier buses, are used. The devised algorithm to solve 5 bus and 30 bus systems has been run and results are obtained desirably.

Keywords: High Voltage Direct Current link, Sequential method, Gauss Seidel, Direct Current, Alternating Current

1. Introduction

Electricity was first used commercially in the late 1870s. Thomas Alva Edison invented the first electricity system. The initial electric power system was a DC system, which consisted of DC generators that fed just 59 consumers within a 1.5-kilometre radius through wires. The limitations of DC systems, such as voltage drop and substantial power

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losses, were discovered with the advent of motors. In 1886, Westinghouse got patents for transformers and AC distribution systems in order to reduce this risk. The disagreements arose because of the differences between in AC and DC systems. However, because of the limitations of DC systems, AC prevailed, and DC systems were eventually phased out. Because it is possible to raise voltage using a transformer, and it is a simple, durable, and diverse system, AC became increasingly practicable. AC systems have seen a number of advancements and upgrades. Rene Thury, a Swiss engineer, was the first to build an HVDC transmission system, which he termed the Thury system. The major aspect of this system is that it uses series DC generators with constant current control, as opposed to AC systems that use constant voltage and changing current. Thury's system was decommissioned in 1938 due to safety concerns. With the passage of time, individuals began to consider ways to boost the voltage in order to obtain the lowest possible loss and drop. It was feasible to convert AC to DC with the development of mercury arc valves. In 1954, the first HVDC connection was established between Sweden and the Swedish island of Gotland, spanning around 70 kilometres where AC lines were not viable. HVDC is chosen for long distance transmission due to the limitations of HVAC systems, such as reactive power losses, stability, and current carrying capability[1].

Sequential and Unified AC/DC power flow techniques are the two most common. The extended variable method is a form of unified method in which the solution vector is extended with DC variables and then solved all at once. In sequential method, the AC and DC systems are solved separately which means AC and DC equations should be solved separately in each iteration. The sequential approach is used, in which the Alternating Current and Direct Current systems are solved independently and afterwards coupled by infusing an equivalent amount of actual and reactive power into the termination of AC buses [2]. This study uses the modified Gauss - Seidel technique to illustrate a sequential technique to solve AC/DC power flow in 5 and 30 bus systems.

2. AC-DC Power Flow Analysis

When HVDC transmission is integrated into an AC electrical network, several features change, particularly in terms of power flow and sustainability. The cornerstone of electrical power system calculations is load flow analysis, which is crucial and important in system planning, operational planning, and design. As a result, the HVDC transmission lines must be accurately modelled and integrated into the AC/DC system's power flow analysis.

The AC–DC power flow problem may be solved in two ways: (1) simultaneously or unified, and (2) sequentially or alternating [3]. The unified approach, also known as the simultaneous method, incorporates and regulates the DC and AC equations while concurrently analysing the entire set. Combining both AC and DC system equations into a single set of nonlinear algebraic equations is a simple and direct use of this technique. In each iteration, the sequential approach solves the AC power equations [4-6] and the DC system equations individually, then solves them sequentially using the interface variables obtained from the AC load flow until convergence is achieved. The equivalent circuit of the converter under steady state operation is shown in the figure 1.

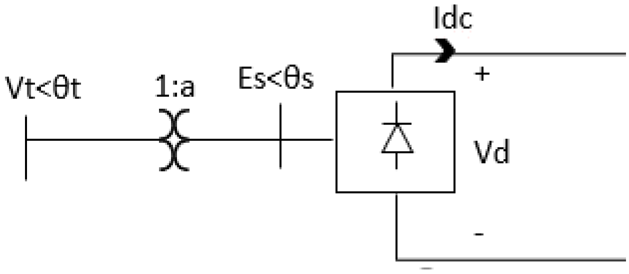

Figure 1. Equivalent circuit of the converter under steady state operation

Where ,

$Vt\angle\theta t$ - Magnitude and angle of the terminal bus bar of the converter

a - Converter transformer tap ratio

$Es\angle\theta s$ - Magnitude and angle of the secondary side of the converter transformer

Vd, Idc - DC voltage and DC current respectively

The equations pertaining to DC are:

$$\text{Vdrec} = \frac{3\sqrt{2}}{\pi} \text{Nrec arec Etrec } \cos\varphi\text{rec} = \text{Vdorec } \cos\varphi\text{rec} \quad (1)$$

$$\text{Vdrec} = \text{Vdorec } \cos\alpha - \frac{3}{\pi} \text{Xcrec Nrec Idc} \quad (2)$$

$$\text{Vdinv} = \frac{3\sqrt{2}}{\pi} \text{Ninv ainv Etinv } \cos\varphi\text{inv} = \text{Vdoinv } \cos\varphi\text{inv} \quad (3)$$

$$\text{Vdinv} = \text{Vdoinv } \cos\gamma - \frac{3}{\pi} \text{Xcinv Ninv Idc} \quad (4)$$

$$\mathrm{Idc} = \frac{\mathrm{Vdrec} - \mathrm{Vdinv}}{\mathrm{Rdc}} \tag{5}$$

The subscripts 'rec' and 'inv' in these equations designate the rectifier and inverter sides, respectively. And Rdc refers to the resistance of the HVDC link.

In an HVDC ink there are a total of 9 unknowns associated with it. The solution vector Xc is given by,

$$\mathrm{Xc} = [\mathrm{Vdrec}\ \mathrm{Vdinv}\ \mathrm{Idc}\ \mathrm{arec}\ \mathrm{ainv}\ \varphi\mathrm{rec}\ \varphi\mathrm{inv}\ \cos\alpha\ \cos\gamma] \tag{6}$$

According to the equation (2.6), there are a total of 9 unknowns that must be associated with the HVDC link. But from equations (2.1) to (2.5), there are only 5 equations which is not sufficient to find 9 unknowns. Thus, out of 9 unknown variables 4 must be specified before in order to find the remaining variables. Several combinations are considered. The combinations of interest are

Combination 1: α , Pdrec , γ , Vdinv

Combination 2: arec , Pdrec , ainv , Vdinv

Combination 3: α , Vdrec , γ , Pdinv

In sequential AC/DC power flow is Alternating Current and Direct Current systems are solved individually and are linked by infusing actual and reactive powers at the termination of AC buses. The modified Gauss Seidel method for solving is shown below.

The flowchart for modified Gauss Seidel method of solving combination 1 where α , Pdrec , γ , Vdinv are specified is shown in figure 2.

Where,

α is the triggering angle in degrees

Pdrec is the rectifier side active power in MW

γ is the extinction angle in degrees

Vdinv is the inverter side voltage in kV

The flowchart for modified Gauss Seidel method of solving combination 2 where a_{rec} , P_{drec} , a_{inv} , V_{dinv} are specified is shown in figure 3.

Where,

a_{rec} is the transformer tap ratio at the rectifier

P_{drec} is the rectifier side active power in MW

a_{inv} is the transformer tap ratio at the inverter

V_{dinv} is the inverter side voltage in kV

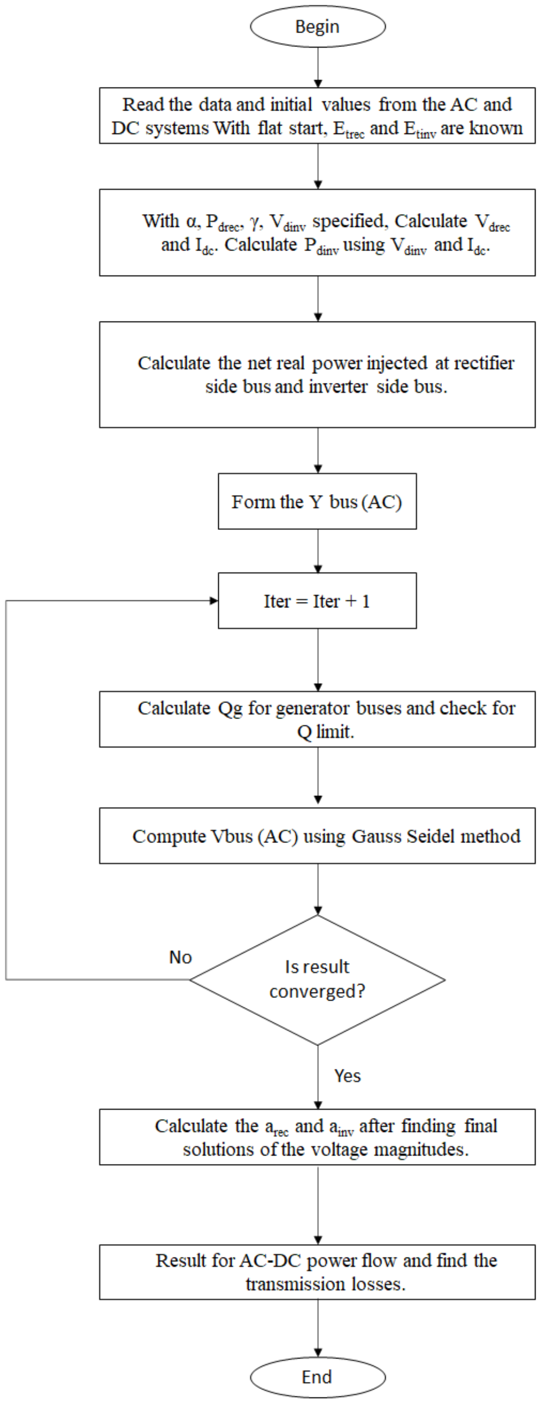

Figure 2. Flowchart of modified Gauss Seidel for combination 1

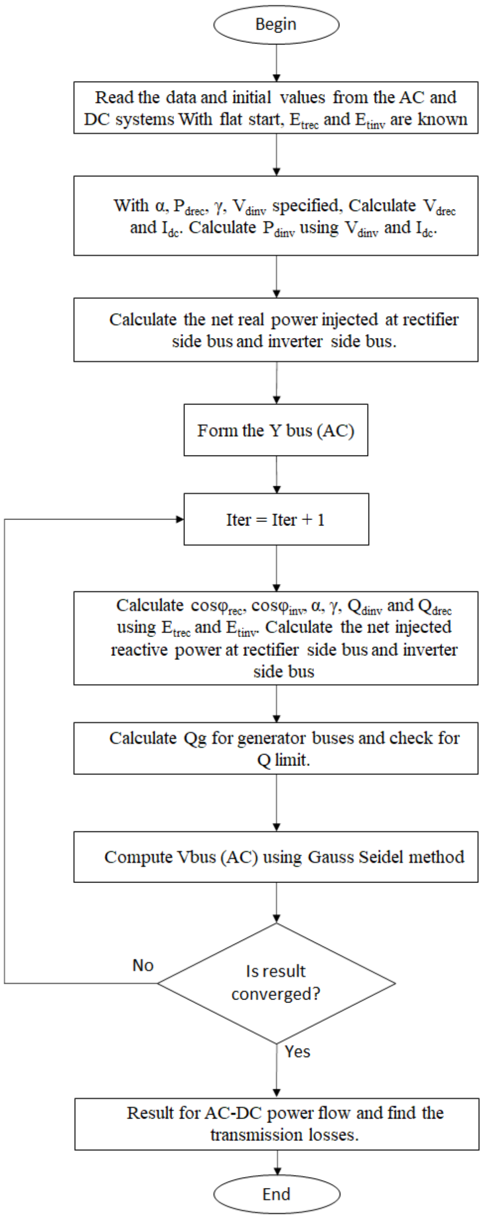

Figure 3. Flowchart of modified Gauss Seidel for combination 2

The flowchart for modified Gauss Seidel method of solving combination 3 where α , Vdrec , γ , Pdinv are specified is shown in figure 4.

Where,

α is the triggering angle in degrees

Pdinv is the inverter side active power in MW

γ is the extinction angle in degrees

Vdrec is the rectifier side voltage in kV

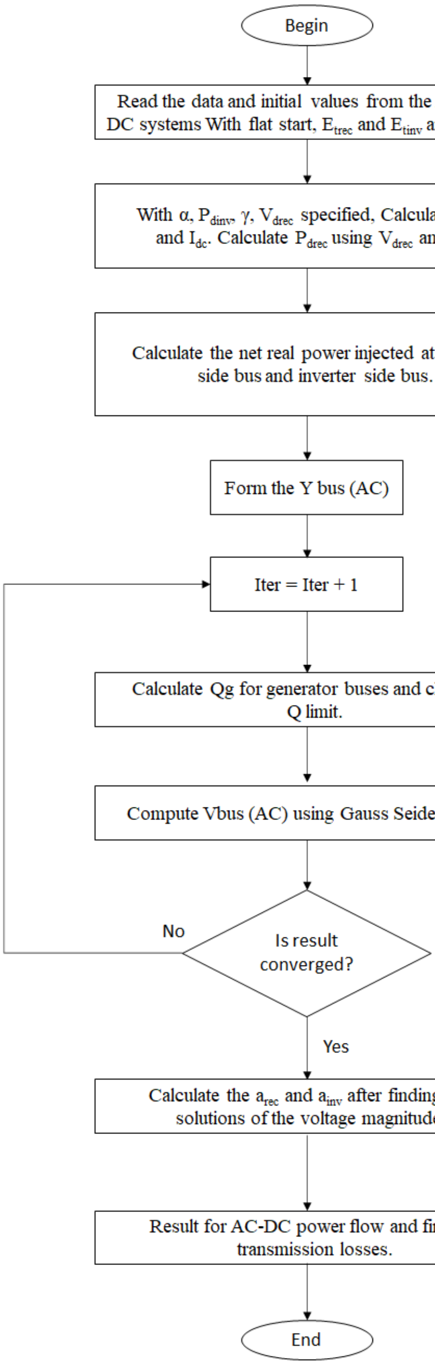

Figure 4. Flowchart of modified Gauss Seidel for combination 3

3. Results and Discussion

A sample system of 5 bus and 30 bus system are taken where the HVDC link is connected between 4th and 5th bus of 5 bus and 9th and 28th buses of 30 bus system. Other corresponding information regarding this connection is as follows: Rdc = 10.0 Ω; Nrec = Ninv = 2; 3/π Xcrec = 3/π Xcinv = 6.0 Ω. The sample 5 bus and 30 bus system are shown in Figure 4 and 5 respectively [7].

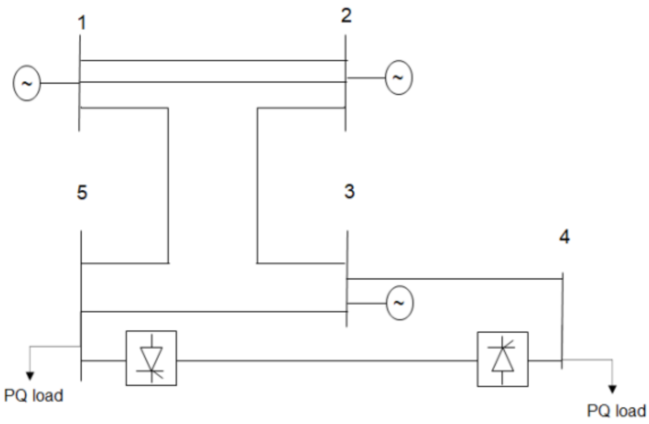

Figure 4. Sample 5 bus system

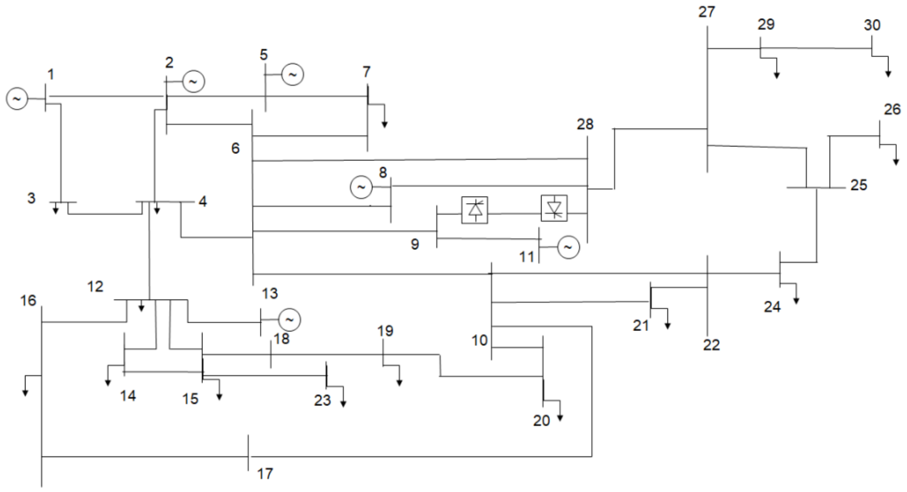

Figure 5. Sample 30 bus system

The results of power flow analysis using Gauss Seidel method for 5 bus system for different combinations are tabulated in Table 1 and the results of power flow analysis using Gauss Seidel method for 30 bus system for different combinations are tabulated in Table 2

Table 1. G-S results of 5 bus system for combination 1, 2 and 3

Bus no.	Combination 1 Pdr=100MW, α = 5, γ = 18,Vdi =250KV				Combination 2 Pdr=100MW, ar=1, ai=1,Vdi=250KV				Combination 3 Pdi=100MW, α=5, γ=18,Vdr=250KV			
	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)
1	1.0000	0	0.7846	-0.5143	1.0000	0	0.7027	-0.3323	1.0000	0	0.7924	-0.5271
2	1.0000	1.3662	0.5	-0.1946	1.0000	1.8222	0.5	-0.1988	1.0000	1.3485	0.5	-0.1822
3	1.0013	-1.4352	1	1.5000	1.0000	-0.8870	1	1.1167	0.9997	-1.4485	1	1.5
4	0.8258	-6.8386	-2.15	-0.8133	0.8549	-6.6075	-2.15	-0.6572	0.8225	-6.8698	-2.1665	-0.8212
5	0.9167	-6.3119	0.1345	-0.7784	0.9424	-6.2181	0.1345	-0.4710	0.9149	-6.3462	0.15	-0.7871
Iteration	29				9				29			

Table 2. G-S results of 30 bus system for combination 1, 2 and 3

Bus no.	Combination 1 Pdr=100MW, α = 5, γ = 18,Vdi =250KV				Combination 2 Pdr=100MW, ar=1, ai=1,Vdi=250KV				Combination 3 Pdi=100MW, α=5, γ=18,Vdr=250KV			
	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)	|V| (pu)	Θ (deg)	Pinj (pu)	Qinj (pu)
1	1.0500	0	2.4560	0.1690	1.05	0	1.4684	-0.0098	1.05	0	2.4595	0.1688
2	1.0338	-5.1372	0.3586	0.0569	1.0338	-3.0115	0.3586	-0.1359	1.0338	-5.1452	0.3586	0.0599
3	1.0241	-8.1436	-0.0240	-0.0120	1.0296	-4.6672	-0.024	-0.012	1.0239	-8.1541	-0.024	-0.012
4	1.0172	-9.8065	-0.0760	-0.0160	1.023	-5.6874	-0.076	-0.016	1.017	-9.8195	-0.076	-0.016
5	1.0058	-13.897	-0.6964	0.0987	1.0058	-10.373	-0.6964	0.0694	1.0058	-13.912	-0.6964	0.0999
6	1.0125	-11.718	0	0	1.0159	-7.0218	0	0	1.0123	-11.733	0	0
7	0.9955	-14.262	-0.6280	-0.1090	0.9977	-10.038	-0.628	-0.109	0.9954	-14.277	-0.628	-0.109
8	1.0230	-12.917	-0.4500	0.3585	1.023	-8.0239	-0.45	0.2596	1.023	-12.936	-0.45	0.3663
9	0.9683	-14.142	-1.0000	-0.2133	0.9745	-8.103	-1	-0.2898	0.9671	-14.177	-1.0165	-0.2212
10	0.9669	-15.659	-0.0580	-0.0200	0.9663	-8.4372	-0.058	-0.02	0.966	-15.688	-0.058	-0.02
11	1.0913	-12.119	0.1793	0.6484	1.0913	-6.0745	0.1793	0.6166	1.0913	-12.151	0.1793	0.6551
12	1.0279	-14.844	-0.1120	-0.0750	1.026	-8.1133	-0.112	-0.075	1.0276	-14.873	-0.112	-0.075
13	1.0883	-13.631	0.1691	0.4713	1.0883	-6.8867	0.1691	0.4866	1.0883	-13.659	0.1691	0.4735
14	1.0067	-15.851	-0.0620	-0.0160	1.0044	-8.761	-0.062	-0.016	1.0063	-15.881	-0.062	-0.016
15	0.9958	-15.879	-0.0820	-0.0250	0.9953	-8.6121	-0.082	-0.025	0.9954	-15.908	-0.082	-0.025
16	0.9945	-15.444	-0.0350	-0.0180	0.9936	-8.405	-0.035	-0.018	0.9939	-15.473	-0.035	-0.018
17	0.9695	-15.819	-0.0900	-0.0580	0.9689	-8.655	-0.09	-0.058	0.9687	-15.848	-0.09	-0.058
18	0.9727	-16.562	-0.0320	-0.0090	0.9734	-8.7988	-0.032	-0.009	0.9721	-16.592	-0.032	-0.009
19	0.9624	-16.765	-0.0950	-0.0340	0.9633	-8.9104	-0.095	-0.034	0.9617	-16.795	-0.095	-0.034
20	0.9627	-16.549	-0.0220	-0.0070	0.9632	-8.8527	-0.022	-0.007	0.9619	-16.579	-0.022	-0.007
21	0.9558	-16.154	-0.1750	-0.1120	0.9563	-8.4742	-0.175	-0.112	0.955	-16.183	-0.175	-0.112
22	0.9572	-16.137	0	0	0.9574	-8.5127	0	0	0.9563	-16.165	0	0
23	0.9744	-16.343	-0.0320	-0.0160	0.974	-8.8981	-0.032	-0.016	0.9738	-16.372	-0.032	-0.016
24	0.9546	-16.600	-0.0870	-0.0670	0.9538	-9.1086	-0.087	-0.067	0.9539	-16.629	-0.087	-0.067
25	0.9658	-16.672	0	0	0.9626	-9.544	0	0	0.9652	-16.699	0	0
26	0.9471	-17.139	-0.0350	-0.0230	0.9439	-10.017	-0.035	-0.023	0.9465	-17.166	-0.035	-0.023
27	0.9819	-16.417	0	0	0.9768	-9.786	0	0	0.9814	-16.441	0	0
28	1.0189	-12.339	0.9845	-0.3784	1.0174	-6.9818	0.9845	-0.3161	1.0186	-12.354	1	-0.3871
29	0.9611	-17.752	-0.0240	-0.0090	0.9564	-11.021	-0.024	-0.009	0.9606	-17.778	-0.024	-0.009
30	0.9491	-18.717	-0.1060	-0.0190	0.9442	-12.048	-0.106	-0.019	0.9486	-18.743	-0.106	-0.019
Iteration	159				31				159			

4. Conclusion

This research presents a technique for power flow analysis of integrated AC–DC systems. Utilizing a simplified model of the DC connection, the techniques of integrating the DC link equations into AC system and using modified Gauss–Seidel AC–DC load flow programmes have been provided. The main idea is to utilise the concept of nodal injection on all buses connected to the DC system. Real and reactive powers are expected to be fed into these buses, which will be calculated and solved using an AC–DC equation set.

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