CHAPTER-5

CASE STUDIES AND RESULTS:

To test the convergence of the developed model, a number of case studies were carried out on a simple 6-bus system and the 30-bus system. In each of these test systems a TCSC is incorporated. In all these case studies, a convergence tolerance of 10^{-4} has been chosen. The case studies are elaborated below:

Case 1: This is a base case without a TCSC for the 6-Bus system. The 6-Bus system (Line & Bus Data is attached in Appendix) used for implementing TCSC is shown in Fig 5.1 below. A power flow solution yielded results tabulated in 5.1 and voltage versus bus no plot is shown in Fig 5.2

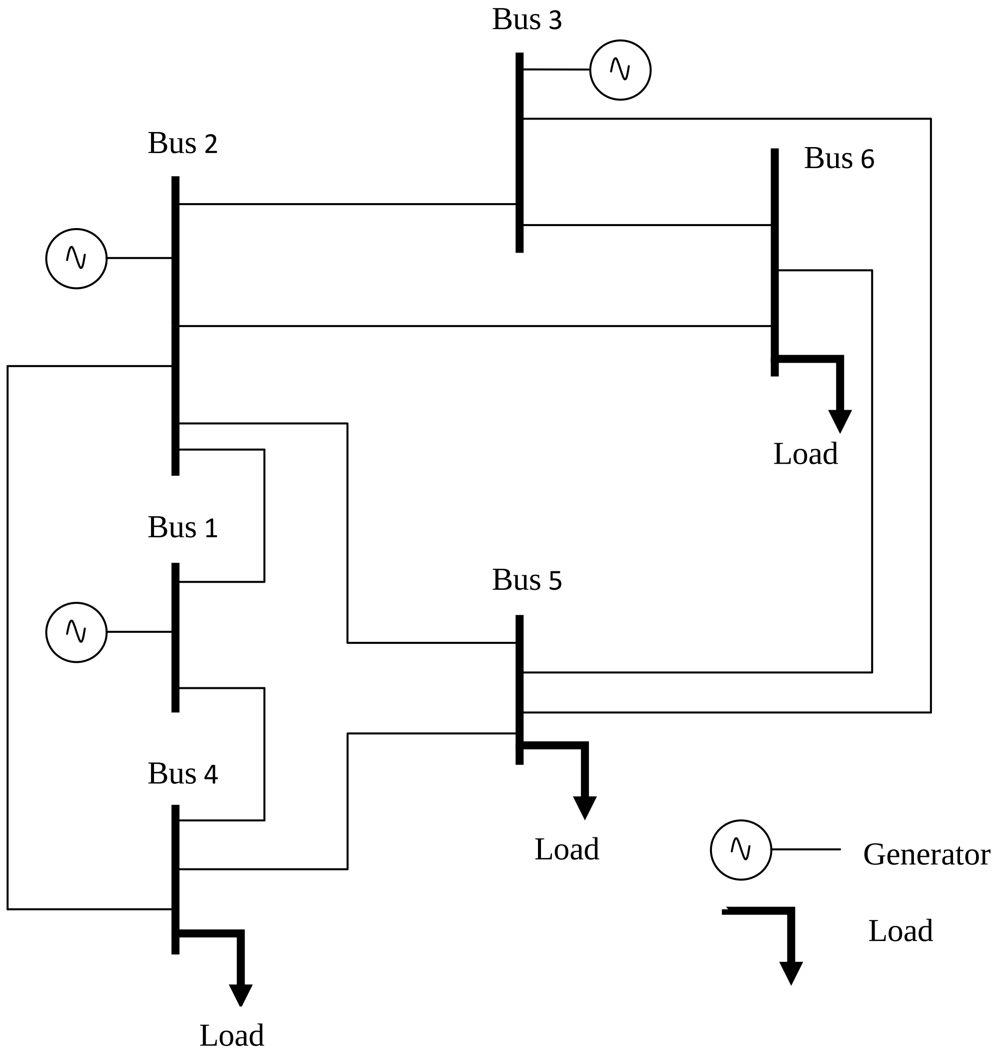

Fig 5.1 6-Bus system used for Implementing TCSC

Table 5.1 Basecase powerflow solution of 6-Bus system

Bus No.	Voltage (p.u.)	Phase angle (Degrees)
1	1.0500	0
2	1.0500	-3.6712
3	1.0700	-4.2733
4	0.9894	-4.1958
5	0.9854	-5.2764
6	1.0044	-5.9475

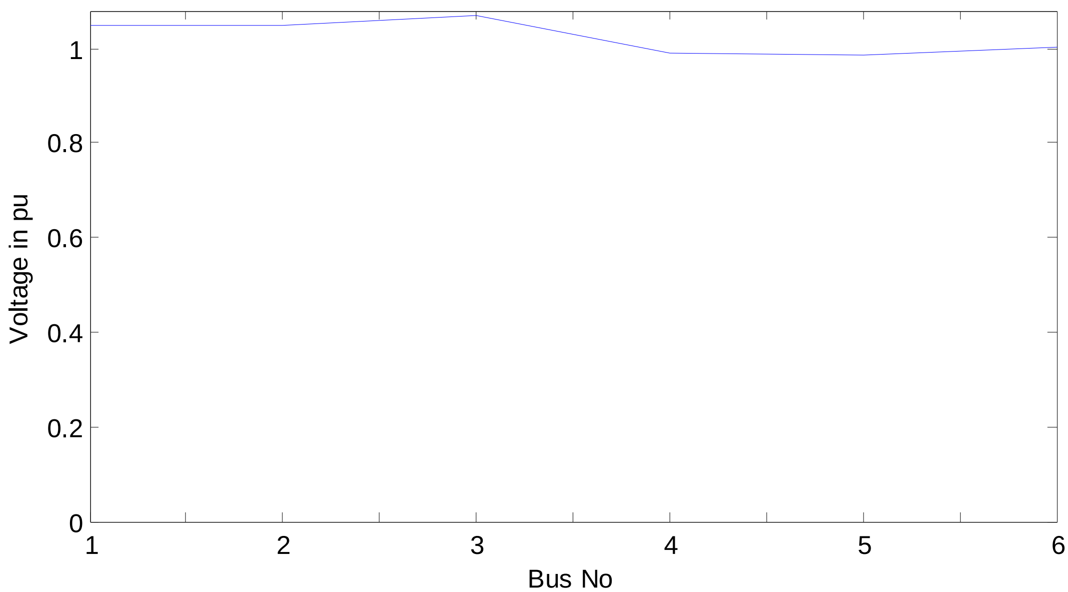

Fig .5.2 Voltage profile for 6-Bus system

Case 2: This is a case with TCSC installed between line 2 and Line 5 and power flow in the line increased from 0.1502 p.u to 0.2 p.u. A power flow solution yielded results tabulated in 5.2 and voltage versus bus no plot is shown in Fig 5.3

Table 5.2 Powerflow solution of 6-Bus system with TCSC

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Susceptance (p.u.)	Firing Angle (Degrees)
1	1.0500	0	B_{TCSC} = 1.8913 p.u. α = 166.57	α =167.54
2	1.0500	-4.3386		
3	1.0700	-4.8825		
4	0.9810	-4.4946		
5	0.9274	-4.3865		
6	0.9932	-6.3944		
P_{2-5} = 0.2 p.u.				

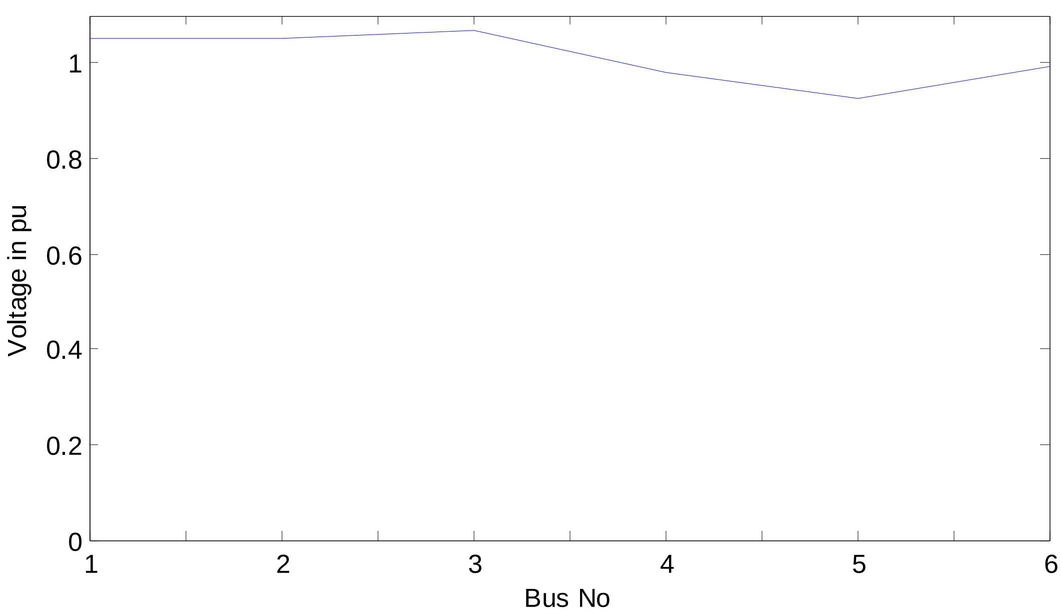

Fig .5.3 Voltage profile for the 6-Bus system with TCSC in line 2-5

The complete Powerflow solution for the 6-Bus system after implementing TCSC is tabulated in Table 5.5. TCSC is placed in Line between 2&5, the percentage increase in Line is 33.15% and the number of iterations is 17 in case of Alfa model and 7 in case of Susceptance model. The Btcsc value in both the cases should be the same which is 1.8913 p.u.

Case 3: This is a case with TCSC installed between line 3 and Line 5 and power flow in the line increased from 0.1802 p.u to 0.25 p.u. A power flow solution yielded results tabulated in 5.3 and voltage versus bus no plot is shown in Fig 5.4

Table 5.3 Powerflow solution of 6-Bus system with TCSC

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Susceptance (p.u.)	Firing Angle (Degrees)
1	1.0500	0	B_{TCSC} = 1.8376 p.u. α = 171.78	α =172.06
2	1.0500	-4.2914		
3	1.0700	-5.4547		
4	0.9799	-4.4687		
5	0.9207	-4.7138		
6	0.9915	-6.7138		
$P_{3\text{-}5}$ = 0.25 p.u.				

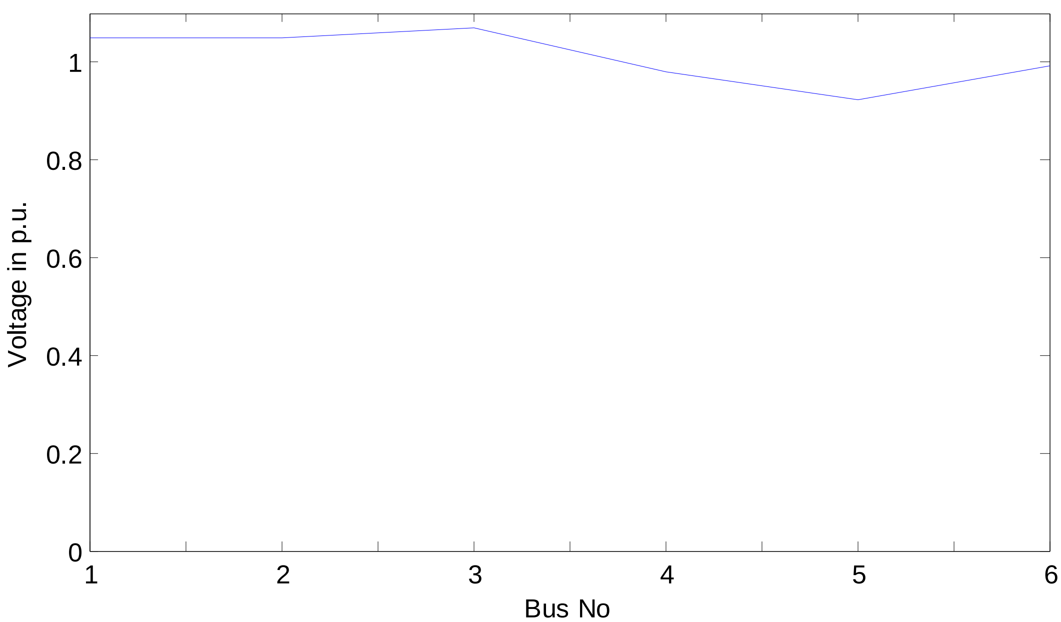

Fig .5.4 Voltage profile for the 6-Bus system with TCSC in line 3-5

The complete Powerflow solution for the 6-Bus system after implementing TCSC is tabulated in Table 5.5. TCSC is placed in Line between 3&5, the percentage increase in Line is 38.73% and the number of iterations is 19 in case of Alfa model and 12 in case of Susceptance model. The Btcsc value in both the cases should be the same which is 1.8376 p.u.

Table 5.5 Complete Powerflow solution obtained in case of 6- bus system

From Bus. no	To Bus. no	Base case Power flow (pu)	Power flow with TCSC (pu)	Percent change in Power flow (%)	Power Flow Solution							
					Alpha Model				Susceptance Model			
					No. of iterations 't'	Time taken (sec)	Btcsc (pu)	Firing angle (degree)	No. of iterations 't'	Time taken (sec)	Btcsc (pu)	Firing angle (degree)
6-Bus system												
2	5	0.1502	0.2000	33.15	17	0.1453	1.8913	167.54	7	0.1513	1.8913	166.57
3	5	0.1802	0.2500	38.73	19	0.1390	1.8376	172.06	12	0.1529	1.8376	171.78

Case 4: This is a base case without a TCSC for the 30-Bus system. The 30-Bus system (Line & Bus Data is attached in Appendix) used for implementing TCSC is shown in Fig 5.5. A power flow solution yielded results tabulated in 5.6 and voltage versus bus no plot is shown in Fig 5.6

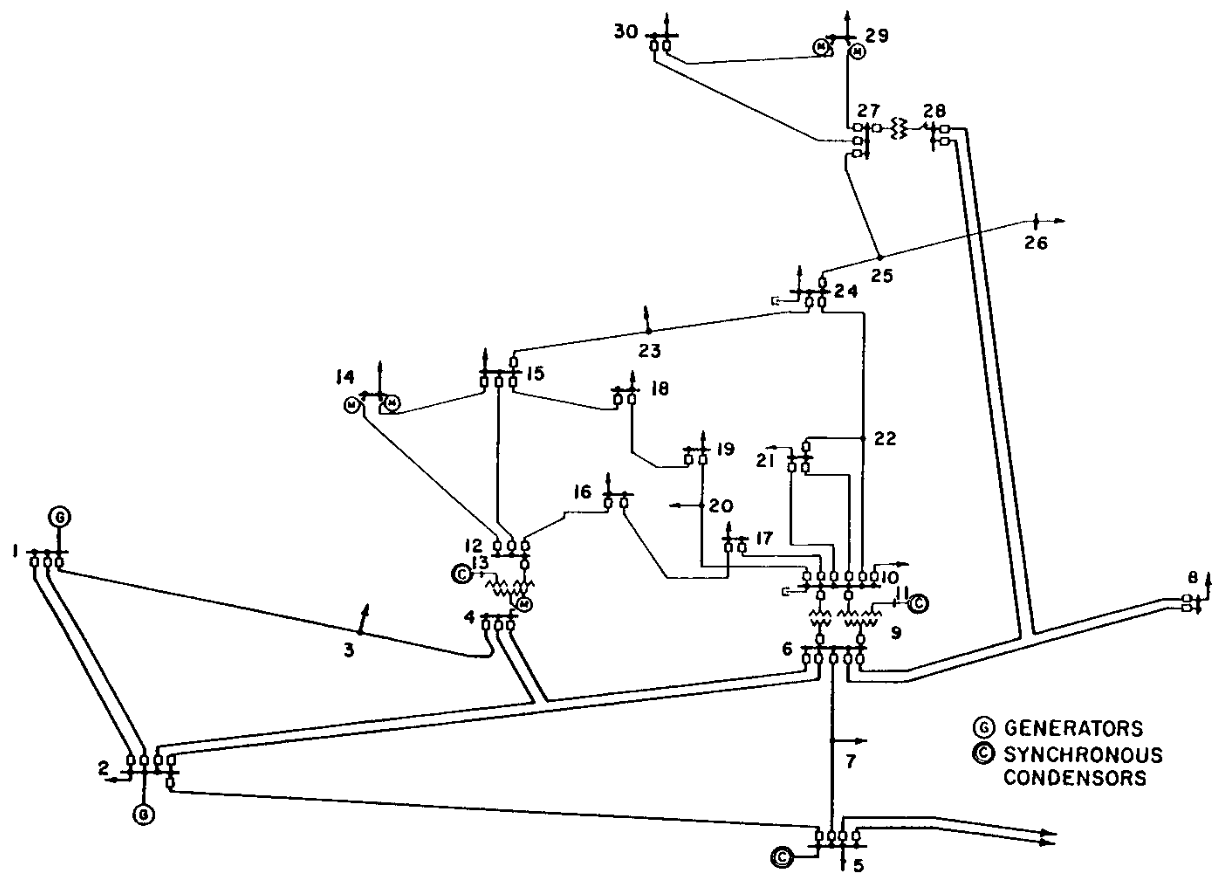

Fig 5.5 IEEE 30-Bus test system

Table 5.6 Basecase powerflow solution of 30-Bus system

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Bus No.	Voltage (p.u.)	Phase angle (Degrees)
1	1.0600	0	16	1.0425	-16.0433
2	1.0430	-5.3539	17	1.0379	-16.2894
3	1.0100	-14.1813	18	1.0261	-17.0422
4	1.0100	-11.8393	19	1.0236	-17.1807
5	1.0820	-14.4177	20	1.0277	-16.9644

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Bus No.	Voltage (p.u.)	Phase angle (Degrees)
6	1.0710	-15.5556	21	1.0307	-16.5359
7	1.0208	-7.5240	22	1.0312	-16.5233
8	1.0119	-9.2741	23	1.0250	-16.8178
9	1.0100	-11.0848	24	1.0193	-16.9140
10	1.0022	-12.8835	25	1.0154	-16.4418
11	1.0500	-14.4177	26	0.9977	-16.8631
12	1.0431	-16.0860	27	1.0216	-15.8888
13	1.0550	-15.5556	28	1.0065	-11.7151
14	1.0401	-16.4229	29	1.0017	-17.1229
15	1.0356	-16.4855	30	0.9902	-18.0088

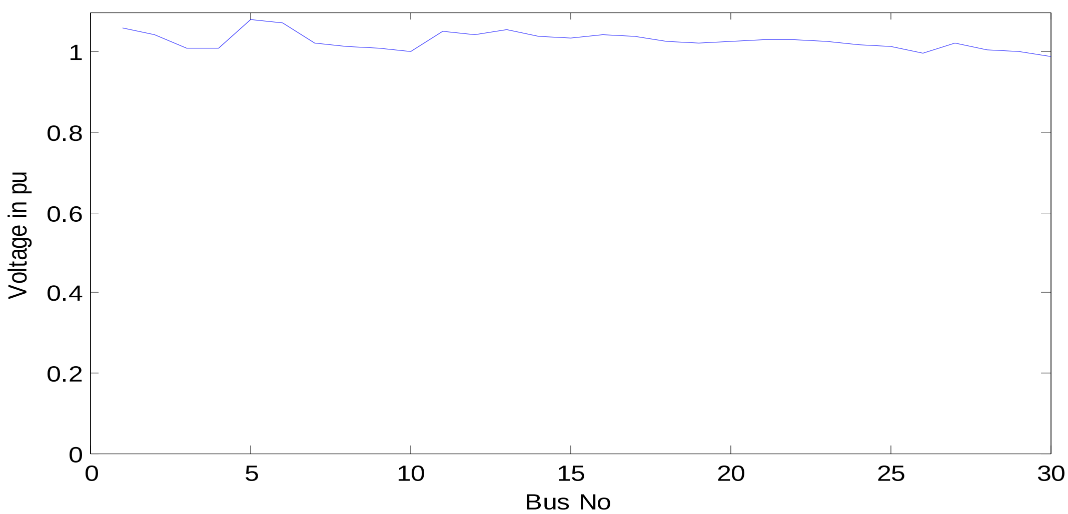

Fig .5.6 Voltage profile for 30-Bus system (base case)

Case 5: This is a case with TCSC installed between line 14 and Line 15 and power flow in the line increased from 0.0142 to 0.016 p.u. A power flow solution yielded results tabulated in 5.7 and voltage versus bus no plot is shown in Fig 5.7

Table 5.7 Powerflow solution of 6-Bus system with TCSC (Line 14-15)

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Bus No.	Voltage (p.u.)	Phase angle (Degrees)
1	1.0600	0	16	1.0222	-15.9474
2	1.0430	-5.3397	17	1.0184	-16.2475
3	1.0100	-14.1358	18	1.0039	-16.9451
4	1.0100	-11.7874	19	1.0022	-17.1256
5	1.0820	-14.3547	20	1.0069	-16.9192
6	1.0710	-15.3828	21	1.0109	-16.5174
7	1.0268	-7.60770	22	1.0112	-16.5015
8	1.0193	-9.37090	23	1.0019	-16.6949
9	1.0137	-11.0983	24	0.9970	-16.8551
10	1.0044	-12.8712	25	0.9902	-16.3539
11	1.0357	-14.3547	26	0.9720	-16.7973
12	1.0241	-16.0587	27	0.9948	-15.7714
13	1.0341	-15.3828	28	1.0098	-11.7088
14	1.0257	-16.4957	29	0.9743	-17.0742
15	1.0121	-16.3029	30	0.9625	-18.0112
P_{14-15} = 0.016 p.u.					
B_{TCSC} = 1.4235 p.u. ; α =169.65					
α =171.35					

The complete Powerflow solution for the 30-Bus system after implementing TCSC is tabulated in Table 5.9. TCSC is placed in Line between 14&15, the percentage increase in Line is 12.67% and the number of iterations is 10 in case of Alfa model and 7 in case of Susceptance model. The Btcsc value in both the cases should be the same which is 1.4235 pu.

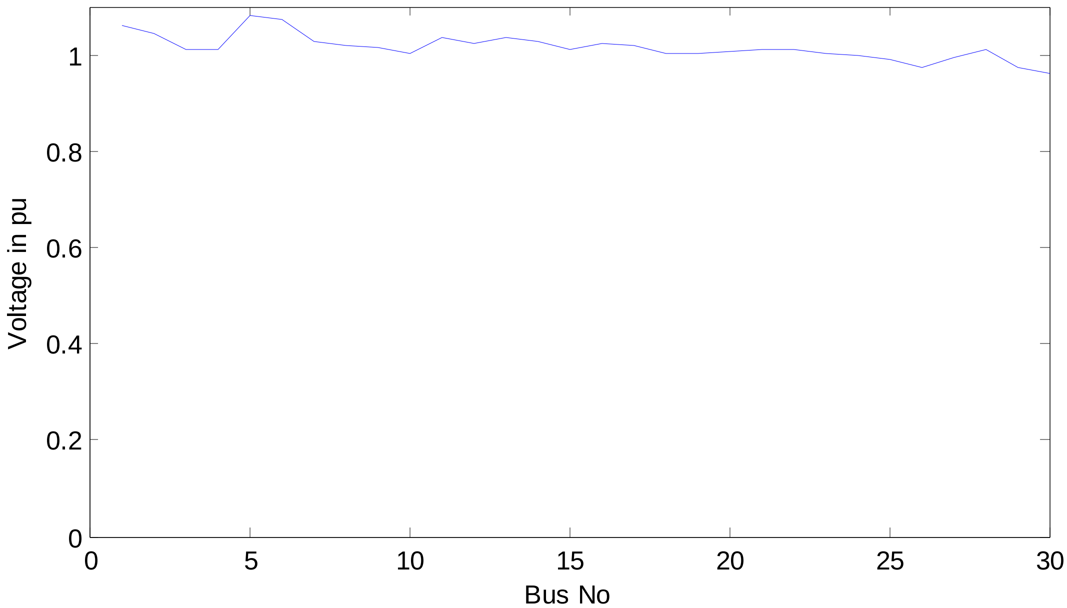

Fig .5.7 Voltage profile for the 30-Bus system with TCSC in line 14-15

Case 6: This is a case with TCSC installed between line 13 and Line 15 and power flow in the line increased from 0.169 p.u. to 0.190 p.u . A power flow solution yielded results tabulated in 5.8 and voltage versus bus no plot is shown in Fig 5.8

Table 5.8 Powerflow solution of 6-Bus system with TCSC (Line 13-15)

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Bus No.	Voltage (p.u.)	Phase angle (Degrees)
1	1.0600	0	16	1.0224	-16.3037
2	1.0430	-5.3960	17	1.0068	-16.3876
3	1.0100	-14.2199	18	0.9490	-15.5412
4	1.0100	-11.8897	19	0.9591	-16.2393
5	1.0820	-14.3680	20	0.9702	-16.2743
6	1.0710	-15.1018	21	0.9912	-16.4453
7	1.0267	-7.7330	22	0.9906	-16.3976
8	1.0192	-9.5267	23	0.9455	-15.1395
9	1.0123	-11.1785	24	0.9652	-16.2676
10	1.0036	-12.9536	25	0.9682	-16.1734
11	1.0272	-14.3680	26	0.9496	-16.6376

Bus No.	Voltage (p.u.)	Phase angle (Degrees)	Bus No.	Voltage (p.u.)	Phase angle (Degrees)
12	1.0074	-16.0624	27	0.9793	-15.8207
13	1.0464	-16.1016	28	1.0072	-11.7616
14	0.9823	-16.0786	29	0.9584	-17.1662
15	0.9380	-13.9504	30	0.9464	-18.1349
P_{13-15} = 0.19 p.u.					
B_{TCSC} = 2.3374 p.u. ; α =171.52					
α =171.37					

The complete Powerflow solution for the 30-Bus system after implementing TCSC is tabulated in Table 5.9. TCSC is placed in Line between 13&15, the percentage increase in Line is 12.43% and the number of iterations is 39 in case of Alfa model and 11 in case of Susceptance model. The Btcsc value in both the cases should be the same which is 2.3374 p.u.

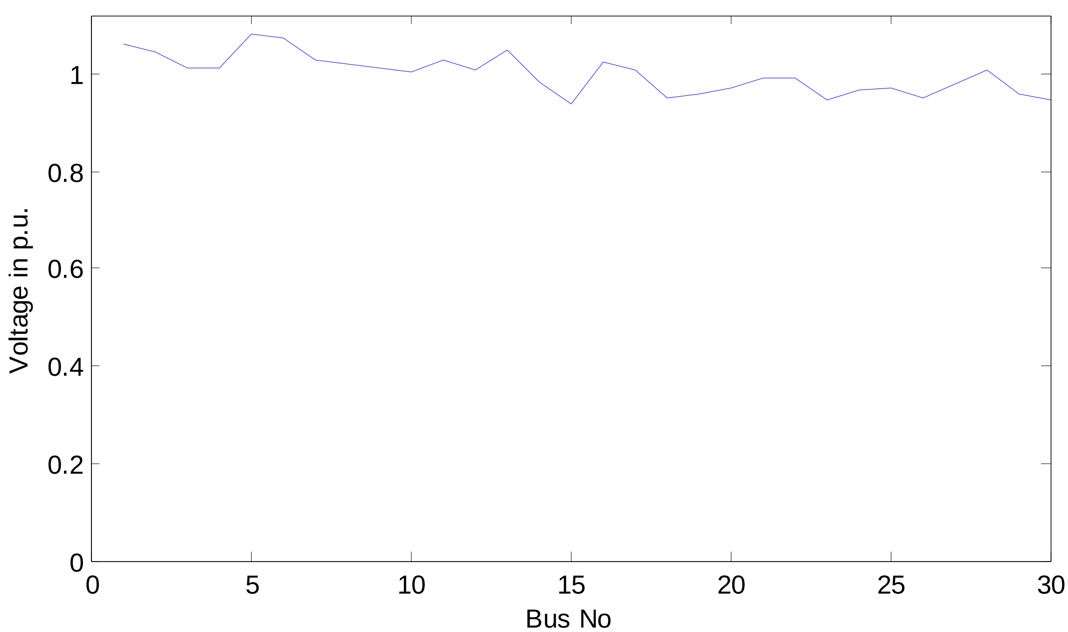

Fig .5.8 Voltage profile for the 30-Bus system with TCSC in line 13-15

Table 5.9 Complete Powerflow solution obtained in case of 30- bus system

From Bus. no	To Bus. no	Base case Power flow (pu)	Power flow with TCSC (pu)	Percent change in Power flow (%)	Power Flow Solution							
					Alpha Model				Susceptance Model			
					No. of iterations 't'	Time taken (sec)	Btcsc (pu)	Firing angle (degree)	No. of iterations 't'	Time taken (sec)	Btcsc (pu)	Firing angle (degree)
30-Bus system												
14	15	0.0142	0.0160	12.67	10	0.162	1.4235	171.35	7	0.140	1.4235	169.65
13	15	0.1690	0.1900	12.43	39	0.256	2.3374	171.37	11	0.185	2.3374	171.52

CHAPTER-6

CONCLUSION:

In this work, a Newton power flow model of the Thyristor Controlled Series Capacitor (TCSC) was developed. The model was appropriately modified to include both the susceptance and the firing angle model of the TCSC. Power flow case studies were carried out with TCSCs installed in different lines in a small six bus system and the IEEE 30 bus system. Power flow solutions were obtained for both the susceptance and the firing angle models. Solution values displayed a close match for both the models. In all the case studies, very good convergence characteristics were obtained, which validates the model

FUTURE SCOPE OF WORK:

Multiple TCSCs can be incorporated into the system by making some changes in the jacobian matrix of the system. An additional row and column are added in the jacobian matrix to incorporate an extra TCSC installed in the system. The susceptance model and firing angle model will have the same number of iterative loops but yield individual alpha values of the TCSCs.

The project can also be developed by using Fast decoupled load flow instead of Newton-Raphson powerflow for fast convergence and computational time.

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APPENDIX

Table 6.1 Line Data for the 6-Bus system [3]

From bus	To bus	R(pu)	X(pu)	BCAP*(pu)
1	2	0.10	0.20	0.020
1	4	0.05	0.20	0.020
1	5	0.08	0.30	0.030
2	3	0.05	0.25	0.030
2	4	0.05	0.10	0.010
2	5	0.10	0.30	0.020
2	6	0.07	0.20	0.025
3	5	0.12	0.26	0.025
3	6	0.02	0.10	0.010
4	5	0.20	0.40	0.040
5	6	0.10	0.30	0.030

BCAP *= half total line charging susceptance

Table 6.2 Bus data for the 6-Bus system

Bus number	Bus type	Voltage schedule(pu V)	P_{gen} (pu MW)	P_{load} (pu MW)	Q_{load} (pu MVAR)
1	Swing	1.05			
2	Generator	1.05	0.5	0.0	0.0
3	Generator	1.07	0.6	0.0	0.0
4	Load		0.0	0.7	0.7
5	Load		0.0	0.7	0.7
6	Load		0.0	0.7	0.7

The above Table 6.1 &6.2 list the input data for the six-bus system used in the Project [3]. The impedances are per unit on a base of 100 MVA.

Table 6.3 Line Data for 30-Bus system [30]

From bus	To bus	R(pu)	X(pu)	BCAP* (pu)	From bus	To bus	R(pu)	X(pu)	BCAP* (pu)
1	2	0.0192	0.0575	0.0264	15	18	0.1073	0.2185	0
1	7	0.0452	0.1652	0.0204	18	19	0.0639	0.1292	0
2	8	0.0570	0.1737	0.0184	19	20	0.0340	0.0680	0
7	8	0.0132	0.0379	0.0042	12	20	0.9360	0.2090	0
2	3	0.0472	0.1983	0.0209	12	17	0.0324	0.0845	0
2	9	0.0581	0.1763	0.0187	12	21	0.0348	0.0749	0
8	9	0.0199	0.0414	0.0045	12	22	0.0727	0.1499	0
3	10	0.0460	0.1160	0.0102	21	22	0.0116	0.0236	0
9	10	0.0267	0.082	0.0085	15	23	0.1000	0.2020	0
9	4	0.0120	0.0420	0.0045	22	24	0.1150	0.1790	0
9	11	0	0.2080	0	23	24	0.1320	0.2700	0
9	12	0	0.5560	0	24	25	0.1885	0.3292	0
11	5	0	0.2080	0	25	26	0.2544	0.3800	0
11	12	0	0.1100	0	25	27	0.1093	0.2087	0
8	13	0	0.2560	0	28	27	0.3960	0.3960	0
13	6	0	0.1400	0	27	29	0.2198	0.4153	0
13	14	0.1231	0.2599	0	27	30	0.3202	0.6027	0
13	15	0.0662	0.1304	0	29	30	0.2399	0.4533	0
13	16	0.0945	0.1987	0	4	28	0.0636	0.2000	0.0214
14	15	0.2210	0.1997	0	9	28	0.0169	0.0599	0.0065
16	17	0.0524	0.1923	0					

BCAP *= half total line charging susceptance

Table 6.4 Bus Data for 30-Bus system

Bus no	Voltage sche-dule(pu V)	P_{gen} (pu MW)	P_{load} (pu MW)	Q_{load} (pu MVAR)	Bus no	Voltage sche-dule(pu V)	P_{gen} (pu MW)	P_{load} (pu MW)	Q_{load} (pu MVAR)
1	1.060	0	0	0	16	1.0	0	0.035	0.018
2	1.043	0.4	0.217	0.127	17	1.0	0	0.090	0.058
3	1.010	0.2	0	0.300	18	1.0	0	0.032	0.009
4	1.010	0	0.300	0	19	1.0	0	0.095	0.034
5	1.082	0	0.942	0.190	20	1.0	0	0.022	0.007
6	1.071	0	0	0	21	1.0	0	0.175	0.112
7	1.0	0	0	0	22	1.0	0	0	0
8	1.0	0	0.058	0.020	23	1.0	0	0.032	0.016
9	1.0	0	0.112	0.075	24	1.0	0	0.087	0.067
10	1.0	0	0	0	25	1.0	0	0	0
11	1.0	0	0.076	0.016	26	1.0	0	0.035	0.023
12	1.0	0	0.228	0.109	27	1.0	0	0.024	0
13	1.0	0	0	0	28	1.0	0	0	0
14	1.0	0	0.062	0.016	29	1.0	0	0.024	0.009
15	1.0	0	0.082	0.025	30	1.0	0	0.106	0.019

Bus no:1- Slack bus, Bus no: 2,3,4,5,6-Generator bus, Rest all are Load busses