A Novel Approach for Simulation of Transmission Line Compensation

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This paper presents an efficient method based on bus power injection for transmission line compensation. In this method, the load flow solution is first obtained using specified generations and loads. The terminal buses connecting the line to be compensated and the compensation level are identified. The differences of the line flows before and after compensation are injected in or out of the two terminal buses. The proposed method has been successfully used to simulate compensation of transmission line by a series capacitor and then by SSSC.

NOTATIONS

ΔP_{ik}, ΔQ_{ik}	active and reactive power injections at k^{th} bus
ΔP_{im}, ΔQ_{im}	active and reactive power injections at m^{th} bus
P_{km}, Q_{km}	active and reactive flows through line from bus k to m
SG_m	complex power generation at m^{th} bus
SL_m	complex power load at m^{th} bus
V_m	complex voltages at m^{th} bus
Y_{mk}	an element of admittance matrix
Y'_{km}	total line charging of line k-m
Af	acceleration factor

1 INTRODUCTION

The demand for electrical energy is increasing steadily in countries on the threshold of industrialization like India. It is not possible always to add new transmission lines to keep pace with growing power plant capacity and energy demand. Finding suitable right-of-ways is another problem. Due to these reasons efforts are being made to use the existing lines more efficiently by improving the steady state and transient stability limits of long lines and the load flows in closely intermeshed networks. The power flow control in conjunction with the FACTS devices[5] has all the capability to meet the challenges of the fast changing energy scenario. The FACTS devices are being designed to remove stability limits, thermal limits, voltage limits and loop flows and meet operators' goals without major system additions.

The line compensation causes the change in system configuration. It is difficult to find the effect of line compensation and outage because of difficulty in carrying out large number of full ac load flow studies[6] in modern large and complex power systems. In literature, the efforts are made to develop the methods to account the effect of line compensation and improve the efficiency and accuracy of these methods.

Initial approach for line outage and compensation simulation was the use of dc load flow. Only the real power flows are considered and thereby these methods are simplest and fastest. Sachdev and Ibrahim[1] proposed a model to account for line outage using power injection while retaining the original system configuration. Denial and Chen[6], suggested the method using the injection of real power at the end of buses of the outaged line. The accuracy of the methods to estimate the effect of line compensation is increased considerably by ac load flow.

El-Marsafaw and Mathur[2] and Mamundar and Berg[3] have suggested methods to calculate bus power injections using sensitivity matrix to simulate line outage simulation. For calculating the values of source compensation, elements of sensitivity matrix of the columns corresponding to the terminal buses of the compensated line are used. This implies that all the changes due to insertion of the compensating device are absorbed at the terminal buses of the compensated line. This will give the correct estimate of the source compensation since the disturbance due to insertion of the compensating device is small. Shandilya et. al. have presented the model for line and transformer outage simulation. The location of FACTS devices in the power system network has been identified in [7,8].

In this paper, the capacitor and SSSC (Static Synchronous Series Compensator) are considered as the compensating devices. The line compensation and the line outage differ on the level of disturbance. Therefore, we do not require to calculate the local solution in the vicinity of the compensated line, before obtaining its global solution.

In this paper, an efficient and accurate method for transmission line compensation is presented. In this method, the load flow solution is first obtained using specified load flow data. The base case Jacobians are retained. The terminal buses of the line to be compensated and the compensation level are identified. The differences of the line flows before and after compensation are injected in or

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out of the two terminal buses. Using these injected values of power, load flow solution iteration is carried out. The parameter settings of the compensating device are obtained when the line flows are obtained within the limits. The proposed method is applied to simulate number of line compensations for 30-bus IEEE test system, using capacitor and SSSC as the compensating devices.

2 MATHEMATICAL MODEL OF SSSC

The SSSC connected between i^{th} and j^{th} bus shown in Fig. 1, is a synchronous voltage source inverter connected in series with the line through transformer. It emulates an inductor (or capacitor) when compensating voltage is quadrature leading (or lagging) to the current. Therefore, it provides controllable compensating voltage over an identical capacitive and inductive range independent of the line current magnitude. The SSSC is capable of interchange of active and reactive powers with the power system. However, the size of the energy source is quite small when reactive power compensation is intended.

The SSSC is represented as a series-connected voltage source which is modeled as an ideal voltage source $\mathbf{V_s}$ in series with a reactance X_s as shown in Fig. 2.

$$\mathbf{V_i'} = \mathbf{V_s} + \mathbf{V_i} \qquad (1)$$

where $\mathbf{V_i'}$ represents a fictitious voltage behind the series reactance.

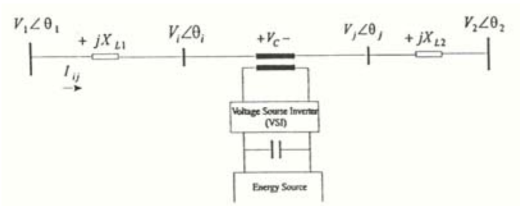

Fig. 1 Schematic arrangement of SSSC

The series voltage source is controllable in magnitude and phase, i.e.

$$\mathbf{V_s} = rV_i e^{j\gamma} \qquad (2)$$

Where $0<r<r_{max}$ and $0<\gamma<2\pi$.

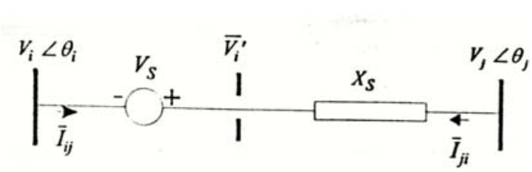

Fig. 2 Modeling of SSSC

The injected source current is expressed as $\mathbf{I_s}=\mathbf{-jV_s}/X_s$ corresponds to the injected source currents. The injection powers S_{is} and S_{js}, are expressed as

$$S_{is} = \mathbf{V_i(-I_s)^*}$$

$$S_{js} = \mathbf{V_j\,(I_s)^*} \qquad (3)$$

The apparent power supplied by the voltage source expressed as an equivalent to SSSC is given by

$$\mathbf{S_{vsi} = V_s I^*_{ij}} \qquad (4)$$

3 SIMULATION METHODOLOGY AND ALGORITHM

The line compensation is resulted into the changes in the system configuration. The system configuration is altered when the compensation is affected in any of the transmission line. To account the effect of the line compensation, a methodology is proposed in which instead of modifying the Y-bus and jacobians of the system, the injected bus powers are modified while the Y-bus and jacobians corresponding to the pre-compensated network are retained. The injected bus powers are evaluated as the difference between the post compensated and pre-compensated line flows values. The injected complex power at any bus m is expressed as-

$$S_m = SG_m - SL_m \qquad (5)$$

The amount of source compensation at the terminal buses of the compensated line are calculated, and the process of convergence is further accelerated by using an acceleration factor, Af, such that

$$P_{im}^{i+1} = P_{mk}^{i} + Af\,(P_{mk}^{i} - P_{mk}^{i-1})$$

$$Q_{im}^{i+1} = Q_{mk}^{i} + Af\,(Q_{mk}^{i} - Q_{mk}^{i-1})$$

$$P_{ik}^{i+1} = P_{km}^{i} + Af\,(P_{km}^{i} - P_{km}^{i-1}) \qquad (6)$$

$$Q_{ik}^{i+1} = Q_{km}^{i} + Af\,(Q_{km}^{i} - Q_{km}^{i-1})$$

The value of the acceleration factor lies between 0.5 and 1.

The proposed algorithm is described briefly in steps as follows:

a) The base case Jacobian is formulated and the load flow solution corresponding to the specified loads and generations is obtained.

b) Select the transmission line to be compensated and calculate the source compensation of the terminal buses of the line to be compensated.

c) Obtain the load flow solution corresponding to the injected source compensations and base case Jacobian.

d) Compute the line flow of the compensated line and compare it with the required flow.

e) If the line flow is within the tolerable limits, line compensation values and the settings of the compensated device are obtained. Otherwise, the source compensation at the terminal buses is modified using eq. (6) and go to step (c).

4 RESULTS AND DISCUSSION

The proposed method was applied on IEEE 30-bus test system. After having the load flow solutions using NR method, the line between bus 13 and bus 12 is identified, for which the reactive line flow is desired to be increased by 10% through compensation. By the proposed power injection method while retaining the base case Jacobians, the flow of the line becomes (12+j36.597) MVA from the (12+j33.989) MVA. The voltages of bus 13 and bus 12 do not change significantly. The increase in the flow in this line results in the decrease in the flow in line between bus 12 and bus 4, which becomes from 14.376 MVAR to 13.293 MVAR. Whereas, the other adjacent line flows and adjacent bus voltages are not affected significantly. The above results are shown in Table 1(a). The results for the desired 10% increase in the reactive power flow on the line between buses 10 and 21 are presented in Table 1(b). The final line flow is decided by the convergence of the load flow, which results in the difference in the desired and the actual line flow after the compensation. When the above compensation is affected by SSSC, its corresponding parameter settings are shown in Table 2.

To demonstrate the effectiveness of the proposed method, the results are compared with NR method using Y-bus modification for both series capacitor and SSSC.

The lines to be compensated are selected from those having appreciable amount of pre-compensated line flow and can be loaded further below its rated capacity. First, the study was carried out using series capacitor offering 0.02 pu reactance and the results are summarized in Table 3. Then, SSSC model was included and the results are summarized in Table 4. The SSSC parameters are calculated to give the effect as that of 0.02 pu reactance by series capacitor in the respective lines for comparison. The corresponding SSSC parameter settings are presented in Table-5. The salient points are summarized as follows -

a) Both real and reactive line flows of the lines are changing. The effectiveness of the compensation depends on both the real and reactive pre-compensated line flows and the X/R ratio.

b) The accuracy of the method is reasonably good and the solution converges between 2-4 iterations.

c) The values of MVAR and MW obtained using the proposed simulation and NR method are in close agreement.

d) The error involved in the terminal voltage magnitudes and phase angles using the proposed simulation and the NR method is less than 0.25%, which is not significant.

5 CONCLUSION

An efficient and accurate method is developed for line compensation simulation using the concept of power injection at the terminal buses. The method has the advantage in the sense that base case Y-bus and Jacobian are retained and no refactorization is required. The accuracy of the method is reasonably good and the solution converges between 2-4 iterations. The method is tested successfully and the SSSC parameters are obtained on the basis of load flow resulted using power injection. The proposed simulation methodology is suited to study the effect of compensation and can be extended to study the compensation effect due to other FACTS devices also.

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Table-1: Pre-compensated and post-compensated line and bus parameters using Proposed Algorithm for the IEEE 30 bus system

Table-1(a) : 10% increase in reactive VARS on line connected between buses 13 and 12

Bus i	**Bus j**	**Pre-compensated V $\angle\delta$ values** **Bus i**	**Bus j**	**Pre-compensated Line flow**	**Post-compensated V $\angle\delta$ values** **Bus i**	**Bus j**	**Post-compensated Line flow**
13	12	1.088 ∠-12.006	1.045 ∠-12.853	12 + j33.9893	1.088∠-12.010	1.041 ∠-12.859	12.000+j36.597
12	4	1.045 ∠-12.853	1.026∠-8.409	-32.016+j 14.376	1.041∠-12.859	1.025∠-8.399	-32.006+j13.293
12	14	1.045 ∠-12.853	1.031 ∠-13.695	7.288+j2.297	1.041∠-12.859	1.027∠-13.707	7.287+j2.299
12	15	1.045 ∠-12.853	1.026 ∠-13.905	18.196+j6.129	1.041∠-12.859	1.022∠-13.917	18.186+j6.136
12	16	1.045 ∠-12.853	1.034 ∠-13.518	7.331+j2.151	1.041∠-12.859	1.031∠-13.526	7.334+j 2.217

Table-1(b) : 10% increase in reactive VARS on line connected between buses 10 and 21

Bus i	**Bus j**	**Pre-compensated V $\angle\delta$ values** **Bus i**	**Bus j**	**Pre-compensated Line flow**	**Post-compensated V $\angle\delta$ values** **Bus i**	**Bus j**	**Post-compensated Line flow**
10	21	1.037∠-13.760	1.024∠-14.191	15.6404 + j10.6991	1.034∠-13.752	1.021∠-14.173	15.591+j11.246
10	6	1.037∠-13.760	1.021∠-9.800	-13.655-j3.941	1.034∠-13.752	1.021∠-9.793	-13.612-j4.320
10	9	1.037∠-13.760	1.042∠-12.032	-29.622-j4.734	1.034∠-13.752	1.038∠-12.020	-29.499-j3.448
10	20	1.037∠-13.760	1.020∠-14.568	9.062+j4.298	1.034∠-13.752	1.018∠-14.570	9.021+j4.094
10	17	1.037∠-13.760	1.031∠-13.900	5.248+j5.627	1.034∠-13.752	1.028∠-13.897	5.200+j5.261
10	22	1.037∠-13.760	1.024∠-14.170	7.526+j5.050	1.034∠-13.752	1.021∠-14.155	7.499+j5.237
21	22	1.024∠-14.191	1.024∠-14.170	-1.976-j0.751	1.021∠-14.173	1.021∠-14.155	-2.029-j1.282

Table-2: Parameter Settings of SSSC for the cases discussed in Table-1

Case No. in Table-1	Value of γ (degrees)	Value of r	Q_{si}	Q_{sj}	P_{si}	P_{sj}
1(a)	-0.000002	0.0000	2.6080	0.00000	0.00000	0.00000
1(b)	-5.162973	-0.000522	0.5473	0.048840	-0.0494	-0.004769

Table-3: Comparison of results of Proposed Algorithm with NR Load Flow for the IEEE 30 bus system using Capacitor as Compensating Device

Reactance of series capacitor (pu)	Power Compensated (MW + j MVAR)	Compensated Line between		Absolute magnitude and voltage phase angle using Simulation		Absolute magnitude and voltage phase angle using NR		Pre-compensated Line Flow (P+jQ)	Post-compensated Line Flow (P+jQ) using	
		Bus 1	Bus 2	Bus 1	Bus 2	Bus 1	Bus 2		Simulation	NR
0.02	-1.069109 + j5.453757	8	6	1.023 ∠ -10.381°	1.020 ∠ -9.787°	1.023 ∠ -10.185°	1.022 ∠ -9.814°	-20.9768 + j10.1913	-21.906 + j15.964	-22.046 + j15.645
0.02	-0.658329 – i0.787414	9	6	1.042 ∠ -12.070°	1.021 ∠ -9.800°	1.037 ∠ -11.885°	1.021 ∠ -9.798°	-19.6217 + j18.8044	-19.952 + j18.483	-20.190 + j18.017
0.02	1.606634 – i0.022568	10	21	1.037 ∠ -13.756°	1.023 ∠ -14.230°	1.034 ∠ -13.768°	1.023 ∠ -14.080°	15.6404 + j10.6991	16.712 + j10.710	17.247 + j10.677
0.02	0.091634 + j3.433482	11	9	1.081 ∠ -10.963°	1.040 ∠ -12.023°	1.081 ∠ -11.067°	1.040 ∠ -12.025°	9.9084 + j20.3609	9.999 + j21.788	10 + j23.794
0.02	-1.030995 + j0.592261	12	4	1.045 ∠ -12.942°	1.025 ∠ -8.404°	1.043 ∠ -12.649°	1.025 ∠ -8.415°	-32.0156 + j14.3755	-32.691 + j14.595	-33.047 + j14.968
0.02	0 + j2.946736	13	12	1.088 ∠ -11.994°	1.042 ∠ -12.843°	1.088 ∠ -12.166°	1.048 ∠ -12.890°	12 + j33.9893	12 + j35.201	12 + j36.936
0.02	0.369577 + j0.161249	28	27	1.016 ∠ -10.352°	1.032 ∠ -13.987°	1.016 ∠ -10.360°	1.033 ∠ -13.818°	18.5621 + j8.7142	18.817 + j8.898	18.932 + j8.875

Table-4: Comparison of results of Proposed Algorithm with NR Load Flow for the IEEE 30 bus system using SSSC as Compensating Device

Case No. in Table-2 indicating parameter settings of SSSC	Power Compensated (MW + j MVAR)	Compensated Line between		Absolute magnitude and voltage phase angle using Simulation		Absolute magnitude and voltage phase angle using NR		Pre-compensated Line Flow (P+jQ)	Post-compensated Line Flow (P+jQ) using	
		Bus i	Bus j	Bus i	Bus j	Bus i	Bus j		Simulation	NR
1	-2.194146 + j1.235349	4	2	1.026 ∠ -8.480°	1.033 ∠ -4.971°	1.025 ∠ -8.296°	1.033 ∠ -5.018°	-33.8419 + j5.8695	-34.637 + j6.280	-36.036 + j7.105
2	-3.322097 + j1.319850	4	3	1.026 ∠ -8.442°	1.030 ∠ -6.949°	1.025 ∠ -8.113°	1.032 ∠ -7.361°	-65.6145 + j9.9529	-68.549 + j11.240	-68.937 + j11.273
3	-2.736416 + j1.007331	5	2	1.006 ∠ -12.255°	1.033 ∠ -4.985°	1.006 ∠ -11.607°	1.033 ∠ -5.008°	-68.2002 + j4.8581	-69.877 + j5.523	-70.937 + j5.865
4	-2.915507 + j1.786595	6	2	1.021 ∠ -9.905°	1.033 ∠ -4.973°	1.020 ∠ -9.631°	1.033 ∠ -5.019°	-46.6987 + j8.6748	-47.773 + j9.205	-49.614 + j10.461
5	-5.351844 + j2.213758	6	4	1.021 ∠ -9.871°	1.025 ∠ -8.371°	1.020 ∠ -9.440°	1.026 ∠ -8.622°	-59.4324 + j6.4146	-63.702 + j8.284	-64.784 + j8.628
6	1.474509 – i0.366956	6	7	1.021 ∠ -9.790°	1.007 ∠ -11.311°	1.021 ∠ -9.854°	1.007 ∠ -10.990°	34.1706 + j5.8872	35.399 + j5.619	35.645 + j5.520
7	-1.069109 + j5.453757	8	6	1.023 ∠ -10.381°	1.002 ∠ -9.787°	1.023 ∠ -10.185°	1.022 ∠ -9.814°	-20.9768 + j10.1913	-21.906 + j12.964	-22.046 + j15.645
8	-0.658329 – i0.787414	9	6	1.042 ∠ -12.070°	1.021 ∠ -9.800°	1.037 ∠ -11.885°	1.021 ∠ -9.798°	-19.6217 + j18.8044	-19.952 + j18.483	-20.190 + j18.017
9	1.606634 – i0.022568	10	21	1.037 ∠ -13.756°	1.023 ∠ -14.230°	1.034 ∠ -13.768°	1.023 ∠ -14.080°	15.6404 + j10.6991	16.712 + j10.710	17.247 + j10.677
10	0.091634 + j3.433482	11	9	1.081 ∠ -10.963°	1.040 ∠ -12.023°	1.081 ∠ -11.067°	1.040 ∠ -12.025°	9.9084 + j20.3609	9.999 + j21.788	10 + j23.794
11	-1.030995 + j0.592261	12	4	1.045 ∠ -12.942°	1.025 ∠ -8.404°	1.043 ∠ -12.649°	1.025 ∠ -8.415°	-32.0156 + j14.3755	-32.691 + j14.595	-33.047 + j14.968
12	0 + j2.946736	13	12	1.088 ∠ -11.994°	1.042 ∠ -12.843°	1.088 ∠ -12.166°	1.048 ∠ -12.890°	12 + j33.9893	12 + j35.201	12 + j36.936
13	0.369577 + j0.161249	28	27	1.016 ∠ -10.352°	1.032 ∠ -13.987°	1.016 ∠ -10.360°	1.033 ∠ -13.818°	18.5621 + j8.7142	18.817 + j8.898	18.932 + j8.875

Table-5: Parameter Settings of SSSC for the cases discussed in Table-4

Case No.	Value of γ (degrees)	Value of r	Q_{si}	Q_{sj}	P_{si}	P_{sj}
1	-60.6196	0.047865	1.235349	-1.1066536	-2.194146	2.129416
2	-68.3324	0.067979	1.319850	-1.238714	-3.322097	3.302155
3	-69.7903	0.057648	1.007331	-0.670607	-2.736416	2.656902
4	-58.5004	0.065571	1.786595	-1.546893	-2.915507	2.782742
5	-67.5279	0.111088	2.213758	-2.081450	-5.351844	5.313951
6	-76.0249	-0.029145	-0.366956	0.400344	1.474509	-1.463203
7	-11.0911	0.106209	5.453757	-5.427004	-1.069109	1.009682
8	35.8205	-0.017897	-0.787414	0.787414	-0.568329	0.587271
9	-89.1952	-0.029895	-0.022568	0.035417	1.606634	-1.586137
10	1.5288	0.058753	3.433482	-3.433482	0.091634	-0.027006
11	-60.1246	0.021778	0.592261	-0.499334	-1.030995	0.962581
12	0	0.049759	2.946736	-2.946736	0	0.041798
13	66.4280	0.007805	0.161249	-0.139587	0.369577	-0.364106