Proceedings of 8th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8

Optimal Setting and Siting of TCSC and SVC to Enhance Power System Performance

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Abstract

Power transfer capability of a transmission line falls with the length of the line. Loading in the short line and long line is permitted by thermal limit and stability limit respectively. In a power system consisting of long lines and short lines, FACTS devices can be used for partial increase of power transfer in the long line as well as improve the voltage profile of the line. The main objective of this study is to minimize system line loss, sum of line loading ratio by optimal placement of Static Var Compensator (SVC) at bus and optimal placement of Thyristor Controlled Series Compensator (TCSC) in long lines. The system line loss and sum of line loading ratio has been separately minimized with the various combination of both TCSC and SVC. The optimization was done with help of Genetic Algorithm (GA). In this work three cases (only SVC, only TCSC, both TCSC & SVC) are considered for optimal power flow. It is observed that SVC is better in improving voltage profile and reducing line loss. Similarly, for this system TCSC is better for partial increase in power flow of long line but less capable of voltage profile improvement. With combination of both TCSC and SVC there is further reduction of power loss, improvement of voltage profile and decrease in the sum of line loading ratio. The result thus obtained was verified with MATLAB 2013Ra.

Keywords

Transmission Loss Minimization, Voltage Profile Enhancement, Genetic Algorithm (GA), Thyristor Controlled Series Compensator(TCSC), Static Var Compensator (SVC)

1. Introduction

Depending upon the active power and reactive power demand on the load buses, the power flow changes in the transmission line. Hence this will cause the overloading and under loading of some lines. Similarly, the loss in the line also increases with the load demand and voltage constraints of some bus are also violated. If some measures are not taken, then the system enters into verge of instability. Hence to address this problem there are solid state power electronics devices known as FACTS devices which stands for Flexible AC Transmission System that can be installed in the power system network as per our requirement. They can be used to control the power flow by changing the parameters of power systems so that the power flow can be optimized as per need. However, these devices should be installed at certain locations with certain ratings so that our desired objective is fulfilled. Hence, optimal placement of FACTS controller in a power transmission network is of great importance for the maximum utilization of transmission network for improving the system efficiency . The performance of power system can be considerably improved with the help of solid state devices which enables the power flow control as per need.

In the modern power system the competition existing among the electric utilities will cause the numbers of power exchanges which can result different issues during operational phase of power system. If these exchanges are not controlled, some lines may get overloaded and system might become unstable. Hence this problem can be handled by proper use of FACTS technology. It allows for the flexible operation of the existing transmission system without adding new lines. The power handling capacity and the performance of the transmission line can be improved with the FACTS. There are different types of FACTS such as Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), Static Compensator (STATCOM), Unified Power Flow

Controller (UPFC), TCPST (Thyristor Controlled Phase Shifting Transformer) etc [1]. There are many advantages associated with the FACTS devices. Their main function is to control the power by controlling parameters such as impedance, terminal voltages and phase angles. They can control the flow of active and reactive power in the network. They can minimize the congestion in the network. They can reduce power losses and improve the voltage profile. Also these device can improve the both transient stability and small signal stability of the power system.

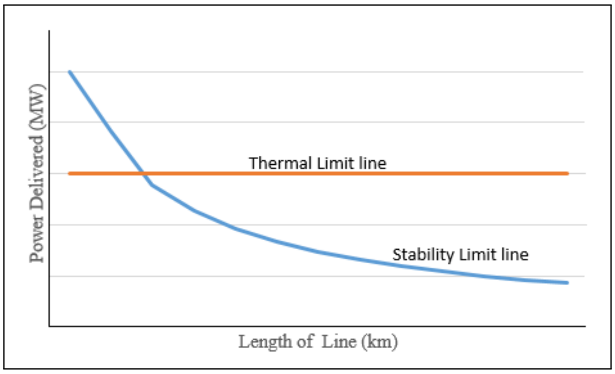

Figure 1: St.Clair Curve

Usually in the power system consisting of long lines and short lines, the long line cannot transfer more power due to stability consideration. The scenario can be observed in the figure 1. It shows that the active power flow through the line is limited by thermal limit in short lines and limited by voltage limit for medium line and limited by stability limit for long lines. Hence due to incapability of more power transfer by long lines can cause the overloading of the short lines in interconnected power system. Hence, we can insert the controllable series compensator in the long lines which can compensate for the inductive reactance of the long lines and hence power through the long line can be increased. Due to increase in the power in the long lines, short lines will get relief and the loading can be managed. The controllable series compensator that we can use is Thyristor Controlled Series Compensator (TCSC). With the introduction of a controllable series capacitor or reactor in series with the transmission line, the line impedance can be varied continuously. Similarly, in the transmission line the voltage can be maintained within the limit by incorporating the shunt compensator. If such devices are not installed, then it will require the reinforcement of the overloaded line whereas the underutilized lines remaining same. Thus, depending upon our requirement we can incorporate the FACTS devices optimally so that the capacity of the line can be made flexible. Some research has used GA for optimal choice and allocation of FACTS devices in multi machine power system and they have simultaneously optimized rating, location and type of FACTS devices [2].

In this study, Genetic Algorithm (GA) is used as a minimization tool for optimal placement of TCSC and SVC so that Line loading management, real power loss reduction and voltage profile enhancement is achieved. The test system under study is Modified IEEE-14 Bus system with two long lines introduced in the system.

2. Problem Formulation

The objective function in this study has two terms, the first term represents the active power loss and second term represents the sum of line loading ratio. Only one objective function is considered at a time during the entire study.

2.1 Objective Function

The objective function is formulated as,

$$MinF = W_1 * [P_L] + W_2 * [SOL] \tag{1}$$

where, W_1 & W_2 are the weight factors whose values are either 1 or 0 as per the requirement.

The first term of the objective function represents the active power loss and is given by equation (2)

$$P_L = \sum_{l=1}^{N_L} G_l(V_i^2 + V_j^2 - 2V_iV_j cos\delta_{ij}) \tag{2}$$

Where,

V_i, V_j are the Voltage magnitude at i^{th} bus and j^{th} bus.

N_L is Number of transmission line.

δ_i,δ_j are the Voltage angle at i^{th} bus and j^{th} bus.

G_l is the Conductance of the l^{th} line.

The second term represents the sum of line loading ratio and is given by equation (3).

$$SOL = \sum_{l=1}^{N_L} (\frac{S_L}{S_Lmax})^n \tag{3}$$

where n=1. In equation (3) S_L corresponds to the actual active power flowing through the line and S_{Lmax} corresponds to the thermal limit for the short line while stability limit for the long lines as that of base case. However, during the study a power factor of 0.9 is used for converting S_{Lmax} into corresponding active power. The stability limit under consideration is taken for power angle corresponding to 30°.

2.2 Constraints

Following inequality constraints includes the limits of the concerned variables.

a) Reactive Power Generation Limit

$$Q_{gimin} \leq Q_{gi} \leq Q_{gimax}$$

where Q_{gimin} and Q_{gimax} are the respective minimum and maximum values of reactive power generation allowed at i^{th} bus.

b) Voltage magnitude limit

$$V_{imin} \leq V_i \leq V_{imax}$$

where V_{imin} and V_{imax} are the respective minimum and maximum values of voltage allowed at i^{th} bus.

c) Limit on reactance offered by TCSC

$$0.8X_L \leq X_{TCSC} \leq -0.3X_L$$

where X_L is the reactance of the transmission line where TCSC is to be connected.

d) Limit on reactive power offered by SVC

$$Q_{SVCmin} \leq Q_{SVC} \leq Q_{SVCmax}$$

where Q_{SVCmin} and Q_{SVCmax} are the respective minimum and maximum values of reactive power generation/absorption by SVC.

2.3 Control Variables

The control variables in the study are the quantities which are to be adjusted so that the minimum value of objective function is obtained. They are reactance offered by TCSC that is obtained by varying the firing angle for compensation of line reactance and the reactive power injected or absorbed at the bus by the Static var compensator that is obtained by varying the firing angle of SVC.

3. Modelling of TCSC and SVC

3.1 Thyristor Controlled Series Compensator

TCSC consists of a Thyristor Controlled Reactor (TCR) in parallel with a capacitor bank and connected in series in the transmission line to compensate the line reactance. TCSC can serve as the capacitive or inductive compensation respectively by smoothly varying the reactance of the transmission line. Figure 2 shows the schematic of TCSC. The reactance offered by TCSC is dependent upon the firing angle input to the TCSC.

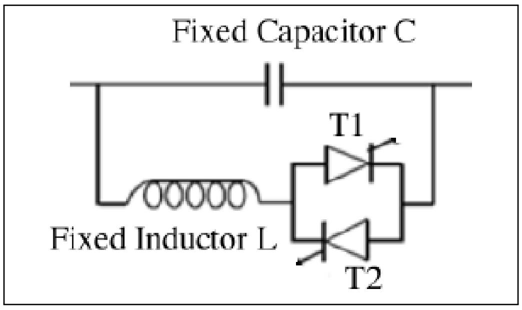

Figure 2: Thyristor Controlled Series Compensator

$$X_{tcr}(\alpha) = \frac{\pi * X_l}{\pi - 2\alpha - sin2\alpha} \tag{4}$$

$$X_{TCSC}(\alpha) = \frac{X_{tcr}(\alpha) * X_c}{X_{tcr}(\alpha) - X_c} \tag{5}$$

Equation (5) gives the variable reactance offered by TCSC for any value of

$$0^\circ \leq \alpha \leq 90^\circ$$

The TCSC is not allowed to operate at the resonance region in this study and firing of TCSC in this study is considered only for capacitive region. In this study for a fixed value of L and C of TCSC, firing angle is controlled to achieve variable reactance of TCSC. The modification in the line reactance due to insertion of the TCSC is shown in equation (6,7).

$$X_{ij} = X_{LINE} + X_{TCSC} \tag{6}$$

$$X_{TCSC} = k * X_{LINE} \tag{7}$$

where k is a numerical coefficient which gives the degree of compensation in transmission line. To avoid overcompensation value of K_{min}= -0.8 and K_{max}=0.3

3.2 Static Var Compensator(SVC)

SVC is a shunt connected device. There are various types of SVC. In this study, Fixed Capacitor Thyristor Controlled Reactor (FCTCR) is used. It consists of a Thyristor Controlled Reactor (TCR) in parallel with a capacitor bank and is shunted at a bus. Compensation provided by SVC can be varied with firing angle. It either injects or withdraws reactive power from the bus to which it is connected and there by maintains the voltage magnitude. Depending upon the firing angle, the reactive power offered by the SVC also varies accordingly. Main benefits of using SVC is that it regulates the bus voltage and also helps in reduction of real power loss in interconnected power system. SVC also provides both inductive and capacitive compensation.

Figure 3 shows the schematic of a Static Var Compensator. The variable reactance offered by the SVC can be obtained with help of equation (8). Reactive power generated/absorbed by SVC can be shown in equation (9).

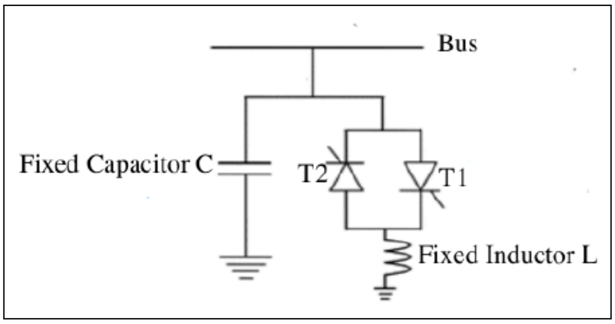

Figure 3: Static Var Compensator

$$X_{svc} = \frac{X_{tcr}(\alpha) * Xc}{X_tcr(\alpha) - Xc} \tag{8}$$

$$Q_{svc} = \frac{V_k^2}{X_{svc}} \tag{9}$$

where V_k is the voltage of the k^{th} bus under consideration.

The range of firing for SVC is set between 0° to 90°. In this study for a fixed value of L and C of SVC, firing angle is controlled to provide the variable compensation. Similarly, the position for its installation is allowed on all bus except the bus containing generators (bus 1 and bus 2).

If capacitive compensation is needed, then we will consider Qsvc as positive while for inductive compensation we will consider Qsvc as negative. However, only capacitive compensation is considered in this study.

4. Methodology

4.1 Flowchart and Algorithm

The flowchart for the proposed study is shown in figure 4. Following algorithm has been developed for the study of the optimal placement of SVC and TCSC.

Step 1: Start

Step 2: Load flow on one of the case where voltage constraint and loading is violated is carried out and this load is considered as 100 %(P and Q) for our case. Load flow initially is done without FACTS device.

Step 3: Load flow result obtained from step 2 is used for computing the power loss and the sum of line loading ratio for that case.

Step 4: Load flow is done with TCSC and SVC at a particular position (TCSC at long line and SVC at a bus other than bus containing Generator) and certain rating value.

Step 5: Objective function is called upon by GA solver tool of MATLAB 2013a for minimization. This will provide the location and rating of SVC and TCSC for minimizing the objective function.

Step 6: If the constrained minimization result is obtained Go to Step 7, otherwise Go to Step 4.

Step 7: Stop

4.2 Genetic Algorithm

Genetic Algorithm is the process of applying biology in engineering. Genetic algorithm which was first proposed by John Holland is based upon evolution theory and genetics. This algorithm is based upon Darwin's Theory. The fundamental concept which is associated with the GA is that it attempts to extract optimum value by minimizing a set of objective function. Usually, Genetic algorithm performs three basic operations. These operations are also called selection, crossover and mutation. These operations are also known as genetic operations which are performed until the minimization is reached. Genetic algorithm generally operates on chromosomes. Each of the chromosomes are given certain fitness value. GA forms new chromosomes in each generation and hence only those chromosomes will survive which had best fitness values. It is robust technique and it is easy to understand but it has slow convergence. However for this study GA optimization solver tool of Matlab 2013Ra is used.

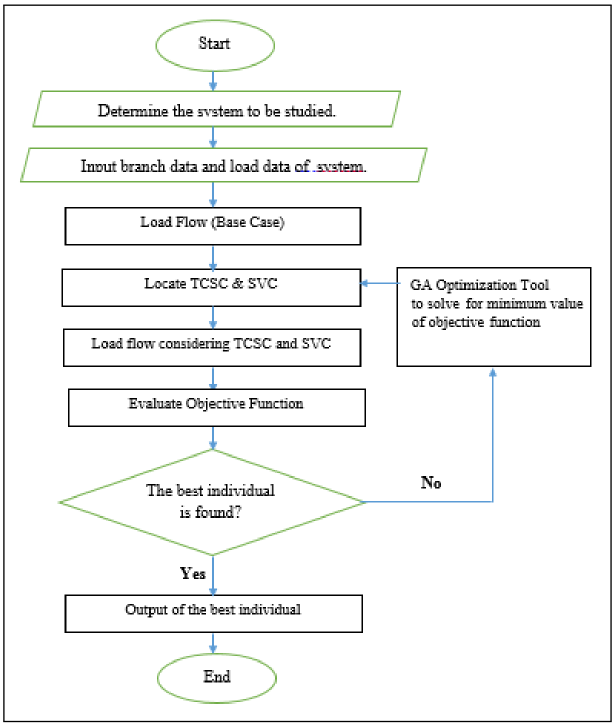

Figure 4: Flowchart Using Genetic Algorithm

5. Simulation and Results

Prior to the placement of TCSC and SVC in the system, power loss and line loadings during overload condition was examined by increasing the load in the system at a certain steps. For the study purpose, real and reactive power loads connected at various load buses were increased simultaneously while the load power factor was kept constant. The load was increased from 70% to 100% of the load of system discussed in section 5.1. At 100% of the load both voltage magnitude and line loading was violated. That is, for study we will create a condition where the system demands for both series and shunt compensation. This case will be our base case throughout the study and it is considered 100%(P&Q) throughout our study and is shown in our result analysis part. The study is done considering upto 2 SVC and 2 TCSC installed in this system. With increase in more devices has minimum change in the objective function under study. The coding were done in MATLAB R2013a.

5.1 Test System Under Study

The test system under study is obtained by modifying the IEEE-14 Bus test system shown in figure 5. All the synchronous compensators are removed so that the system demands for shunt compensation. Further, one long line between bus 1 and bus 5 and another long line between bus 2 and bus 3 are introduced by linear scaling of existing original system for study purpose. Line between bus 1 and bus 5 is Line-2. Line between bus 2 and bus 3 is Line-3. The line lengths of the system shown in figure 5 can be found in various research papers [3]. The thermal limit of long lines under study are considered as 1.83 p.u. Some research has proposed the line limits of the IEEE-14 bus system and hence we have considered the same line rating for all the lines except line 2 and line 3 for our study purpose [4]. Similarly, the other conditions such as generation and loads of the system were not changed. Hence this causes the base case loading of standard IEEE-14 bus and the system under study to be different.

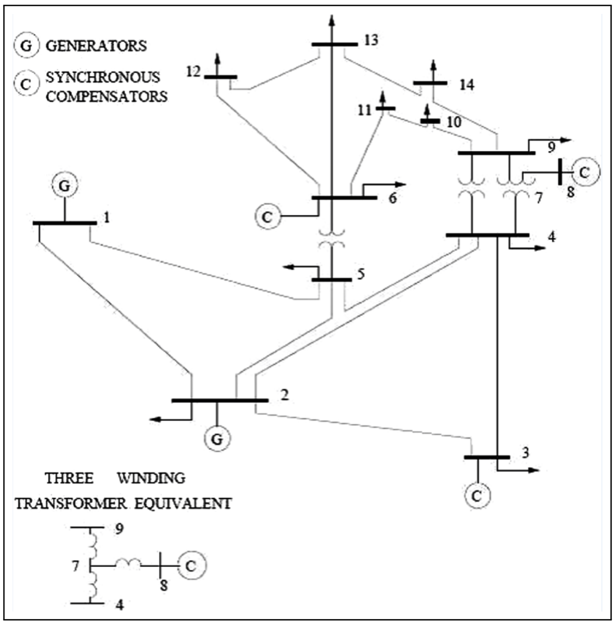

Figure 5: Modified IEEE-14 Bus System

5.2 Study without TCSC AND SVC

This section shows the simulation result at base case loading of system discussed in section 5.1. Figure 6 shows the voltage profile of load bus. It shows that voltages are out of limit and voltage constraint is violated. Table 1 shows the line loss scenario with the increase in loading from 70% to 100% of total load of system. It shows power loss increases with loading.

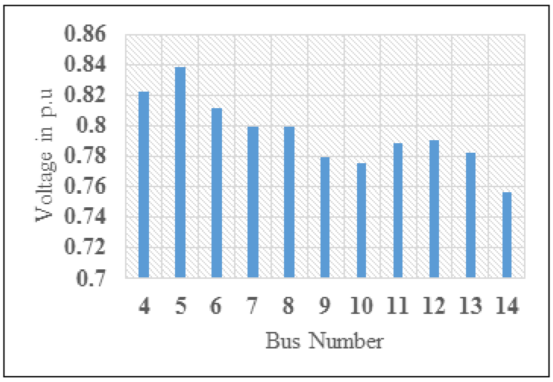

Figure 6: Voltage profile at bus before placement of TCSC and SVC

Figure 7 shows the phase angle condition of the system at base case. It can be observed that the phase angles are within the limit at steady state conditions without addition of TCSC and SVC.

Table 1: Line loss with increased loading

SN	Load%(P and Q)	Overall Line loss
1	70%	0.0968 p.u.
2	80%	0.132719 p.u.
3	90%	0.236115 p.u.
4	100%	0.354075 p.u.

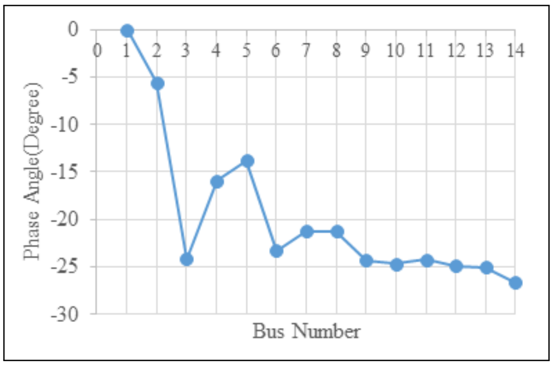

Figure 7: Phase angle condition before placement of TCSC and SVC

Figure 8 shows the line loading ratio of each of the line. Line number 14 corresponds to the connection between compensator and the tertiary of three winding transformer. This part carries zero power during our study. It can be observed from figure 8 that some lines are overloaded while the long lines have enough margin of operation. Hence it requires the redistribution of loadings of the lines so that long line transfers extra power within its margin thereby creating relief in the short lines.

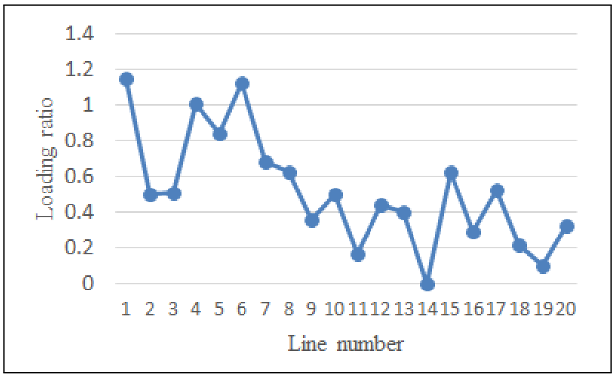

Figure 8: Line loading ratio before placement of TCSC and SVC

5.3 Minimization Study with SVC only

This section shows the simulation result at base case with the inclusion of SVC for power loss minimization. Figure 9 shows the variation of power loss with increase in number of SVC. It can be observed that with addition of 2 SVC drastically reduces the power loss and this value remains almost steady because the voltage are boosted within the limit with more increment of SVC. Hence we will consider study with 2 number of SVC in our base case. From table 2 it can be observed that the power loss reduces by 40.63% with the inclusion of 2 number of SVC. Table 3 gives the optimal location and optimal rating for SVC. Optimal location is at Bus No-5 and Bus No-7, and the optimal rating of SVC for these bus are 0.369 p.u. and 0.4638p.u. respectively. From table 4 it can be observed that sum of line loading ratio also decreased from 10.3443 to 10.1062.

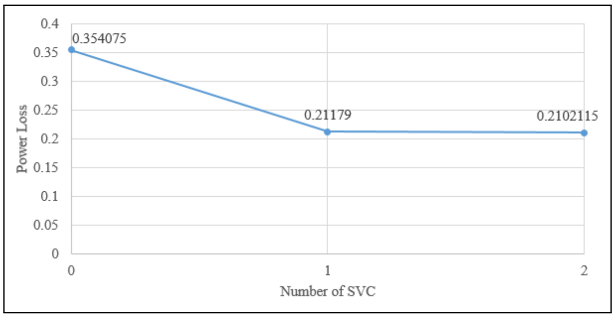

Figure 9: Power Loss(p.u) Variation with number of SVC

Table 2: Losses before and after SVC

Loading	Loss before SVC	Loss after 2 SVC
Base case	0.354075	0.2102115

Table 3: Optimal ratings locations of SVC

Loading	Optimal ratings(p.u.)	locations
Base case	0.369,0.4638	Bus-5,Bus-7

Table 4: Sum of line loading ratio before and after SVC

Loading	Before SVC	After 2 SVC
Base case	10.3443	10.1062

5.4 Minimization Study with TCSC only

This section shows the simulation result at base case with the inclusion of TCSC for sum of line loading ratio minimization. Figure 10 shows the variation of Sum of line loading ratio with number of TCSC. It can be observed from the table 5 that the sum of line loading ratio decreased from 10.3443 to 9.3426 with two number of TCSC. Since our aim in this study is to locate TCSC in the long lines only and the long lines under study are limited to two. Hence we will consider two TCSC for our study purpose. The decrease in sum of line loading ratio is quite more as that compared to SVC case.

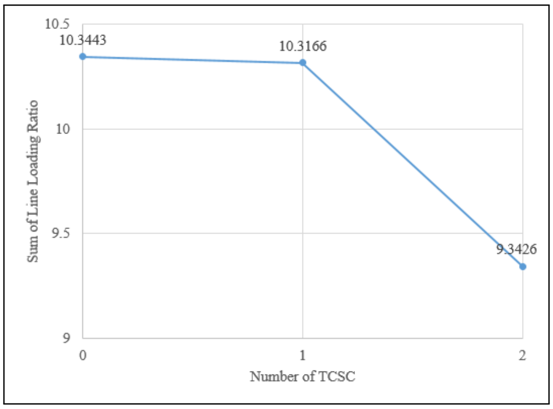

Figure 10: Sum of line loading variation with number of TCSC

Table 5: Sum of loading ratio before and after TCSC

Loading	Before TCSC	After 2 TCSC
Base case	10.3443	9.3426

Table 6: Optimal ratings and locations of TCSC

Loading	Optimal ratings(p.u.)	locations
Base Case	0.0146,0.3159	Line-2,Line-3

Table 7: Losses before and after TCSC

Loading	Before TCSC	After 2 TCSC
Base case	0.354075 p.u.	0.312705 p.u.

Figure 11 shows the voltage profile with the inclusion of TCSC. However, with the TCSC placed on line 2 and 3 the voltage limit is still violated for the system under study. Hence this necessitate SVC to be used along with TCSC. Table 6 shows the location and optimal rating of TCSC without considering voltage constraint. Location for this case is line no 2 and line no 3, and the corresponding rating can be found in Table 6. Similarly, from table 7 it can be observed that inclusion of TCSC has significantly less effect on the overall power loss.

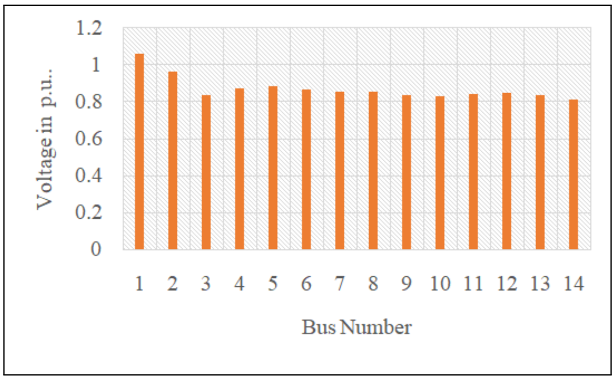

Figure 11: Voltage at each bus with TCSC

5.5 Minimization Study with both TCSC and SVC

5.5.1 Minimization of Power Loss Only

This section shows the simulation result at base case with the inclusion of TCSC and SVC for minimization of Power Loss Only. Table 8 shows the power loss variation with different number of TCSC and SVC. It can be observed that for different combination of TCSC and SVC the objective function is giving different values. Among this four values the minimum is associated with the two SVC and two TCSC. For this case the percentage reduction in power loss is 41.89%. This reduction in power loss is slightly more compared to that of with two SVC only. The optimal locations and the optimal rating for this case is shown in table 7. Phase angle conditions with inclusion of TCSC and SVC for this case is shown in figure 12.

5.5.2 Minimization of Sum of Line Loading ratio only.

This section shows the simulation result at base case with the inclusion of TCSC and SVC for minimization of sum of line loading ratio only. Table 9 shows sum of line loading ratio variation with different number of TCSC and SVC. It can be observed that for different combination of TCSC and SVC the objective function is giving different value. Among this four values the minimum is associated with two SVC and two TCSC. For this case sum of line loading ratio has decreased from 10.3443 to 9.2581. The decrease in this value is more as compared to the individual placement of TCSC and SVC. The optimal location and optimal rating for this case is given in table 9. Voltage profile is shown in figure 13 after inclusion of SVC and TCSC. The line loading ratio of each of the line after placement of TCSC and SVC is shown in the figure 14. Phase angle conditions with inclusion of TCSC and SVC for this case is shown in figure 15.

Table 8: Power loss minimization with different number of TCSC and SVC

Number of FACTS Device	Power Loss (p.u.)	Optimal rating & location
1 SVC & 1 TCSC	0.210249	Bus-7 (0.6805 p.u.), Line-2 (0.0313 p.u.).
1 SVC & 2 TCSC	0.207638	Bus-7 (0.6740 p.u.), Line-2 (0.0345 p.u.), Line-3 (0.0471 p.u.)
2 SVC & 1 TCSC	0.2085357	Bus-9 (0.4775 p.u.), Bus-6 (0.2379 p.u.), Line-2 (0.0292 p.u.).
2SVC & 2 TCSC	0.2057448	Bus-5 (0.4002 p.u.), Bus-9 (0.3532 p.u.), Line-2 (0.0334 p.u.), Line-3 (0.045875 p.u.).

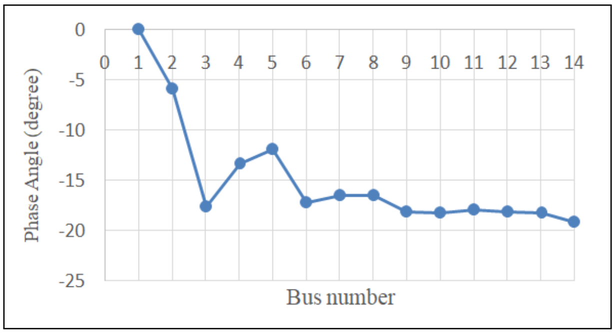

Figure 12: Phase angle condition at bus after placement of TCSC and SVC for minimization of active power loss only

Table 9: Sum of line loading ratio minimization with different number of TCSC and SVC

Number of FACTS Device	Sum	Remarks	Optimal rating(p.u.) & Location
1 SVC & 1 TCSC	10.0318	Constraints Satisfied, but overloading still exists	Bus-9 (0.5617), Line-2 (0.0118).
1 SVC & 2 TCSC	9.32189	Constrained Satisfied and Loading managed	Bus-9 (0.6684), Line-2 (0.0744), Line-3 (0.2165).
2 SVC & 1 TCSC	10.0316	Constraints Satisfied, but overloading still exists	Bus-13 (0.4194), Bus-9 (0.3821), Line-2 (0.0121).
2 SVC & 2 TCSC	9.25814	Constraints satisfied and Loading managed	Bus-13 (0.2280), Bus-9 (0.4702), Line-2 (0.0741), Line-3 (0.2156).

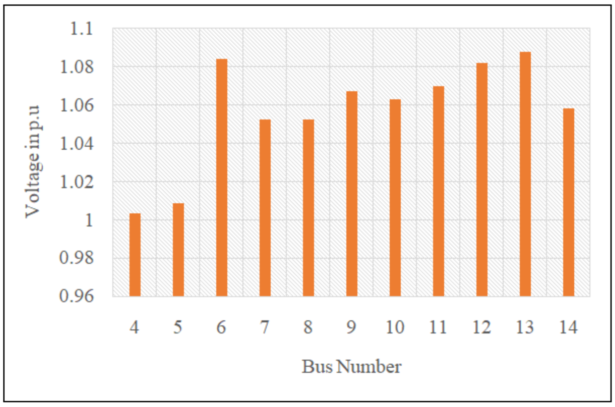

Figure 13: Load bus voltage after placement of TCSC and SVC

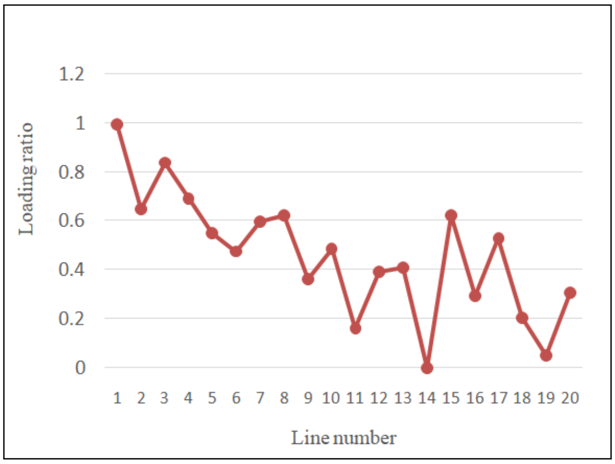

Figure 14: line loading after placement of TCSC and SVC

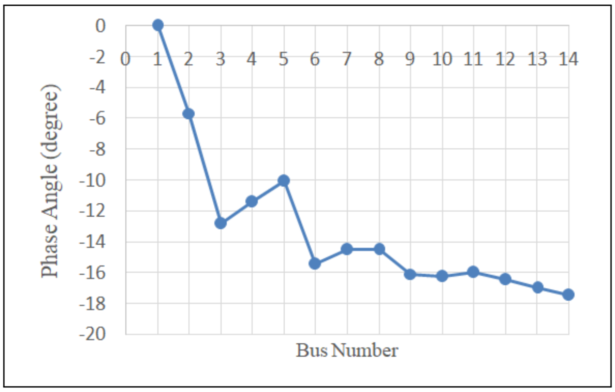

Figure 15: Phase angle condition at bus after placement of TCSC and SVC for minimization of sum of line loading ratio only.

6. Conclusion

Usually the optimal placement of the series and shunt compensator in a power system is a complex problem as there are many possible solution. The study was performed on a modified IEEE-14 bus system. For this study, GA solver of Matlab has been used. The system line loss and sum of line loading ratio has been separately minimized with various combination of both TCSC and SVC. It was observed that the minimum power loss obtained with two number of SVC and two number of TCSC was further decreased as compared to only SVC case. Similarly, it was observed that the minimum sum of line loading ratio obtained with two number of TCSC and two number of SVC was further reduced as compared to individual placement of SVC and TCSC. The results obtained shows that line loss and sum of line loading ratio can be minimized to extent possible from TCSC and SVC.

Minimization of sum of line loading ratio signifies the improved system security and also it indicates loading can be done to some extent higher than the previous with the same transmission lines.

Since the main aim of this study is the minimization of Power Loss and sum of line loading ratio, the objective function was minimized to the extent possible with the help of Genetic Algorithm tool. This study can be extended to other test system using other kinds of optimization techniques. Also from this analysis we can see that TCSC and SVC together perform better in improved performance of the system than using individually.

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