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Optimization of Reactive Power by Using SVC and TCSC Devices for Reducing Transmission Losses

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Abstract

In general the optimization of reactive power is viewed from two aspects: load compensation and voltage support. This is utilized to reduce the total system active power loss or voltage deviation as an objective to compute optimal settings of reactive power output or terminal voltages of generating plants, transformer tap settings and output of other compensating devices such as synchronous condensers and capacitor banks. This paper has considered the setting of flexible AC transmission system (FACTS) devices as additional control parameters using Newton Raphson technique and the impact on system loss reduction in power system. Static models of two FACTS devices consisting of static var compensator (SVC), thyristor controlled series compensator (TCSC) have been included in the problem formulation. The proposed algorithm has been applied to 9-bus test system and IEEE 14-bus system.

Keyword*: Reactive power, SVC, TCSC*

I. Introduction

Almost all bulk electric power is generated, transmitted and consumed in an alternating current (AC) network. Elements of AC systems produce and consume two kinds of power: active power (measured in watts) and reactive power (measured in volt-amperes reactive, or var). Active power accomplishes useful work (e.g., running motors and lighting lamps). Reactive power supports the voltages that must be controlled for system reliability.

It is expected that the secure, efficient and economical operation of power system will become more difficult because of more complex power flow in the future. As a result, the cost reduction and efficiency improvement are needed not only for the power plant operation but also for the power system operation.

Voltage profile is improved by controlling the production, absorption and flow of reactive power throughout the network. Reactive power flows are minimized so as to reduce system losses.

Transmission losses can be calculated based on the natural properties of components in the power system: resistance, reactance, capacitance, voltage, current, and power, which are routinely calculated by utility companies as a way to specify what components will be added to the systems, in order to reduce losses and improve the voltage levels.

The centralized voltage reactive control is one such control which can help not only to keep the system voltages within specified limits but also to preserve the reactive power balances for enhanced security and to decrease the transmission losses for the efficient system operation.

Power flow solution is a solution of the network under steady state conditions subjected to certain constraints under which the system operates. The power flow solution gives the nodal voltages and phase angle given a set of power injections at all buses and specified voltages. Voltage regulation is achieved by controlling the production, absorption and flow of reactive power throughout the network. Reactive power flows are minimized so as to reduce system losses. Sources and sinks of reactive power, such as shunt capacitors, shunt reactors, rotating synchronous condensers and SVC's are used for this purpose. Thyristor Controlled series Compensators are versatile devices that controls the reactive power injection at a bus using power electronic switching components. The reactive source is usually a combination of reactors and capacitors.

The proposed power flow algorithm for reduction of transmission loss incorporating TCSC and SVC devices is independent of the system size. The algorithm uses Newton-Raphson technique.

II. Power Flow Control

The power transmission line can be represented in power system from bus "p" to "q". The active power transmitted betweens bus p and q is given by:

$$P = \frac{Vp\ Vq}{X} \sin(\delta p - \delta q) \qquad \ldots(1)$$

Where V_p and V_q are the voltages at the buses, $(\delta_p\text{-}\delta_q)$ is the angle between the voltages and X is the line impedance.

The power flow can be controlled by altering the voltages at a node, the impedance between the buses and the angle between the end voltages. The reactive power transmitted betweens bus p and q is given by:

$$Q = \frac{Vp^2}{X} - \frac{VpVq}{X} \cos(\delta p - \delta q) \qquad \ldots(2)$$

NEWTON-RAPHSON Technique

The Newton- Raphson technique has proved most successful owing to its strong convergence characteristics. The power flow Newton-Raphson algorithm is expressed by using Jacobian matrix.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} * \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \qquad \ldots(3)$$

Where ΔP and ΔQ are change in active and reactive power, while δ and V are bus magnitude and angle, respectively.

Jacobian is the matrix of partial derivatives of real and reactive power with respect to the voltage magnitude and angles.

III. Modeling of Static VAR Compensator

The Static VAR Compensator (SVC) is the shunt connected FACTS controller whose main function is to regulate the voltage at a given bus by controlling its continuously variable susceptance, which is adjusted in order to achieve a specified voltage magnitude while satisfying constraint conditions. SVC total susceptance model is shown in Fig.1. A changing susceptance B_{svc} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. This model is an improved version of SVC models.

Representation of SVC Susceptance Model

In power system, the SVC can be an adjustable reactance with reactance limit. The equivalent circuit shown in figure1 is used to derive SVC nonlinear power equation and the linearised equation required by Newton`s method.

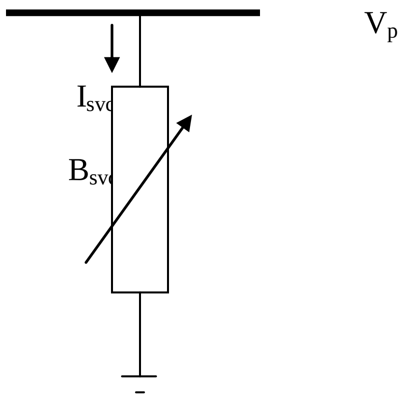


Fig 1. Variable shunt susceptance

Current drawn by the SVC is

$$I_{svc} = jB_{svc}\, V_p \qquad \ldots(4)$$

and the reactive power drawn by the SVC, which is injected reactive power at bus *p*

$$Q_{svc} = Q_p = -V^2 B_{svc} \qquad \ldots(5)$$

The equivalent susceptance Bsvc is taken to be

$$\begin{bmatrix} \Delta Pp \\ \Delta Qp \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & Qp \end{bmatrix} x \begin{bmatrix} \Delta \delta p \\ \Delta Bsvc/Bsvc \end{bmatrix} \qquad \ldots(6)$$

The variable susceptance Bsvc is updated according to

$$B^{(i)}_{svc} = B^{(i-1)}_{svc} + (\Delta Bsvc/Bsvc)^{(i)} \text{ x } B^{(i-1)}_{svc} \qquad \ldots(7)$$

The changing susceptance represents the total SVC susceptance necessary to maintain the nodal voltage magnitude.

IV. Modeling of Thyristor Controlled Series Compensator

The TCSC is based on the concept of a variable series reactance, the value of which is adjusted automatically to constraint the power flow across the branch to specified value. The amount of reactance is determined efficiently using Newton's method. The changing X_{TCSC} is shown in fig 2.

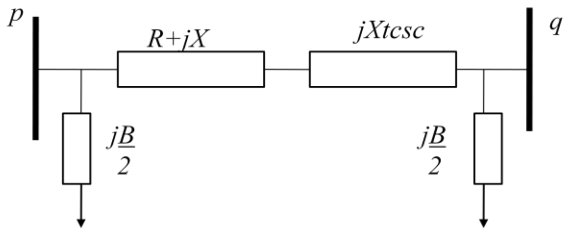


Fig 2. TCSC model with series reactance

The transfer admittance matrix of the variable series compensator is given by

$$\begin{bmatrix} Ip \\ Iq \end{bmatrix} = \begin{bmatrix} jBpp & jBpq \\ jBqp & jBqq \end{bmatrix} x \begin{bmatrix} Vp \\ Vq \end{bmatrix} \qquad \ldots(8)$$

For the inductive operation

$$Bpp = Bqq = -\frac{1}{Xtcsc} \qquad \ldots(9a)$$

$$Bpq = Bqp = \frac{1}{Xtcsc}. \qquad \ldots(9b)$$

The Active and Reactive power equation for bus P are

$$P_p = V_p V_q \, B_{pq} \sin(\delta_p - \delta_q) \qquad (10a)$$

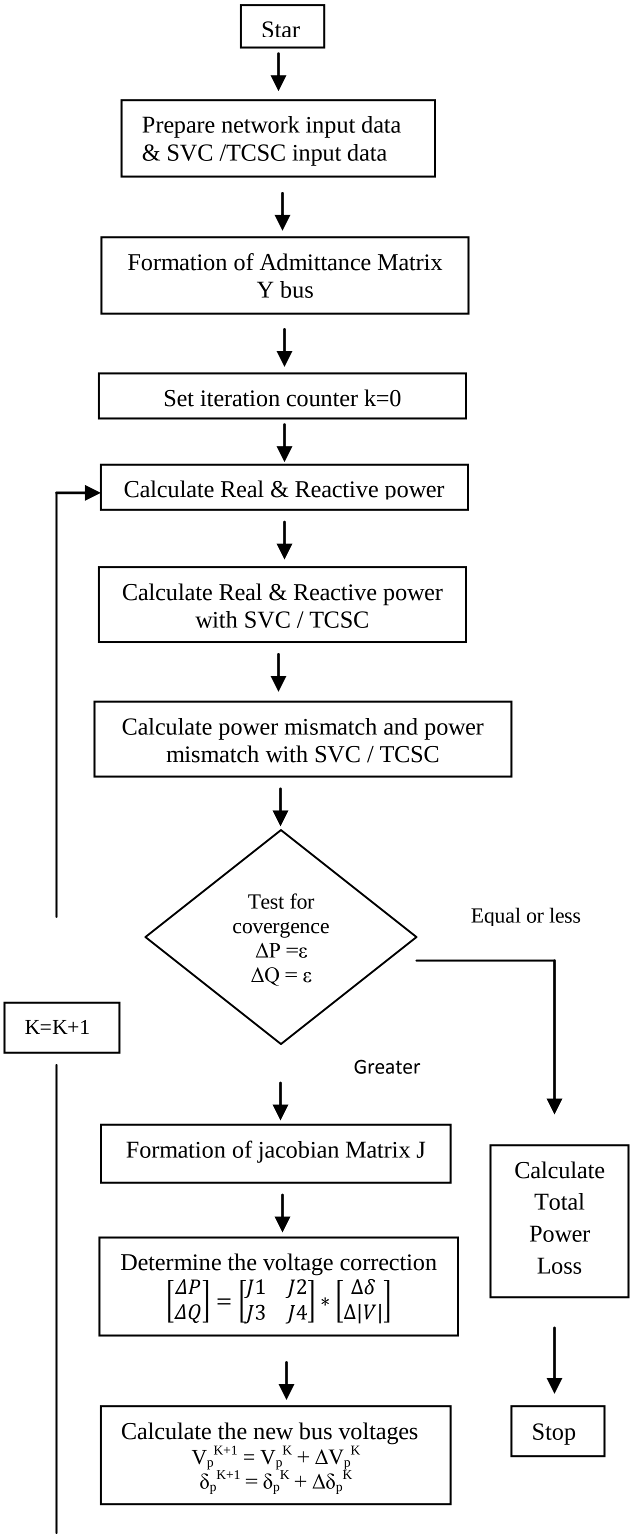
$$Q_p = -V_p^2 B_{pp} - V_p V_q B_{pq} \cos(\delta_p - \delta_q) \qquad (10b)$$

The series reactance ΔX_{tcsc} is the incremental change in the reactance.

$$\Delta X_{tcsc} = X^{(i)}_{tcsc} - X(^{i-1})_{tcsc} \qquad \ldots(11)$$

Updating the X_{TCSC} of the series reactance is given by

$$X^{(i)}_{tcsc} = X(^{i-1})_{tcsc} + (\Delta X_{tcsc}/X_{tcsc})^{(i)} \, X^{(i-1)}_{tcsc} \qquad \ldots(12)$$


Star
Prepare network input data & SVC /TCSC input data
Formation of Admittance Matrix Y bus
Set iteration counter k=0
Calculate Real & Reactive power
Calculate Real & Reactive power with SVC / TCSC
Calculate power mismatch and power mismatch with SVC / TCSC
Test for covergence ΔP =ε ΔQ = ε
Equal or less
Greater
K=K+1
Formation of jacobian Matrix J
Determine the voltage correction $\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix} * \begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix}$
Calculate the new bus voltages $V_p^{K+1} = V_p^K + \Delta V_p^K$ $\delta_p^{K+1} = \delta_p^K + \Delta\delta_p^K$
Calculate Total Power Loss
Stop

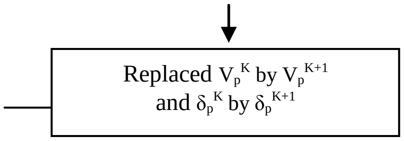


Fig 3. Flow chart for N-R Method with SVC/TCSC

V. Simulation and Result

Case-I: 9 Bus Test System

9-bus test system is used to assess the effectiveness of SVC and TCSC models for reduction of transmission loss. The 9 bus test system consists of 3 generator, 9 buses, 9 branches with 230kV and 100MVA base. The system data is taken from [9].

The placement of SVC has been considered at load buses only SVC is connected at bus 5, bus 6 and at bus 8. TCSC connected between line 9-8, 7-8, and between line 4-6.

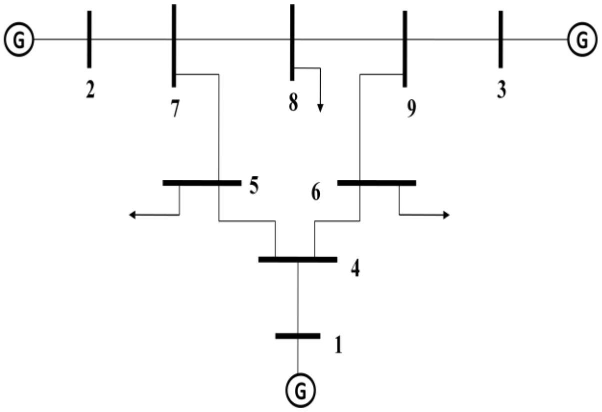


Fig. 4. 9-bus test System.

The SVC absorbs 27.4595MVAr from the bus 8 and keeps the magnitude of voltage at 1 pu. The convergence is obtained after 5 iteration and Bsvc is measured -0.2746 pu.

When SVC is connected to the bus 6 then it absorbs 15.2861MVAr and keeps the voltage at that bus is 1.0 pu and Bsvc equal to -0.1529 pu.

The SVC inject 1.4707MVAr into the bus 5 the transmission loss reduces to 4.5858MW which is more effective than the SVC connected at bus 8 and Bus 6.

Table1
Voltage magnitude and phase angle for 9bus system with and without SVC

Base case			**SVC at bus 8**		**SVC at bus 6**		**SVC at bus 5**	
Ploss5.2996			4.7732		4.6876		4.5858	
Qsvc			27.4595		15.2861		-1.4707	
B =			-0.2746		-0.1529		0.0147	
Bus	**|V| (V)**	**δ Degree**	**|V| (V)**	**Δ Degree**	**|V| (V)**	**δ Degree**	**|V| (V)**	**δ Degree**
1	1.04	0	1.04	0	1.04	0	1.0400	0
2	1.025	9.16	1.025	9.34	1.025	9.16	1.0250	9.1642
3	1.025	4.63	1.025	4.73	1.025	4.64	1.0250	4.6396
4	1.027	-2.21	1.024	-2.22	1.022	-2.22	1.0276	-2.211
5	0.998	-3.98	0.99	-3.99	0.994	-4.01	1.0000	-3.982
6	1.014	-3.68	1.01	-3.69	1.00	-3.63	1.0145	-3.681
7	1.0315	3.63	1.023	3.77	1.03	3.62	1.0318	3.6367
8	1.020	0.68	1.00	0.81	1.02	0.67	1.0202	0.6908
9	1.033	1.94	1.027	2.01	1.03	1.9406	1.0340	1.9459

Table 2
Comparison of results

	Matlab Programming		**Power World Simulator**	
	Power loss (MW)	**Qsvc MVAr**	**Power loss (MW)**	**Qsvc MVAr**
Base case	5.2996	-	5.6	-
SVC at bus 8	4.7732	27.4595	4.9	30.5
SVC at bus 6	4.6876	15.2861	4.7	15.1
SVC at bus 5	4.5858	-1.4707	4.7	-1.5

TCSC device is connected between the bus 9 and bus 8. The active power loss reduces to 4.6323MW and Xtcsc is measured -0.04 pu. The active power flow in line 9-8 increased from 24.6MW to 25.5 MW.

TCSC is used to maintain active power flow from bus 7 to bus 8 which is increased from 76.1MW to 80.2MW. The active power loss reduces to 4.7775 MW and Xtcsc is measured -0.035pu. The active power loss reduces to 4.8819MW when TCSC device is connected between the line 4-6 and Xtcsc measured -0.05pu.

Table3

Voltage magnitude and phase angle for 9bus system with and without TCSC

Base case			**TCSC at 9-8**		**TCSC at 7-8**		**TCSC at 4-6**	
Ploss =5.2996			4.6323		4.7775		4.8819	
Xtcsc			-0.0400		-0.0350		-0.0500	
Bus	**|V| (V)**	**δ Degree**	**|V| (V)**	**Δ Degree**	**|V| (V)**	**δ Degree**	**|V| (V)**	**δ Degree**
1	1.040	0	1.040	0	1.0400	0	1.040	0
2	1.025	9.17	1.025	10.130	1.0250	6.489	1.025	10.
3	1.025	4.63	1.025	3.5323	1.025	7.331	1.025	7.4
4	1.027	-2.2	1.0275	-2.212	1.0276	-2.2	1.026	-2.3
5	0.998	-3.98	1.0014	-3.595	1.0015	-4.8	0.996	-3.4
6	1.014	-3.7	1.0123	-4.09	1.0142	-2.7	1.026	0.2
7	1.031	.637	1.0405	4.6493	1.0335	0.971	1.031	5.3
8	1.020	0.688	1.0418	2.0378	1.0321	4.399	1.021	2.8
9	1.033	1.943	1.0267	0.8193	1.0376	4.647	1.036	4.7

Table 4 Comparison of Results

	Matlab Programming		**Power World Simulator**	
	Power loss (MW)	**Xtcsc (pu)**	**Power loss (MW)**	**Xtcsc (pu)**
Base case	5.2996	-	5.6	-
TCSC at 9-8	4.6323	-0.04	4.9	-0.04
TCSC at 7-8	4.7775	-0.035	5.4	-0.035
TCSC at 4-6	4.8819	-0.05	4.8	-0.05

Case-II: IEEE 14 Bus System

This method is extended to the IEEE 14 bus system. The SVC device is connected to the bus 14 and bus 4. TCSC device is connected between the line 12-13 and line10-11 [3].

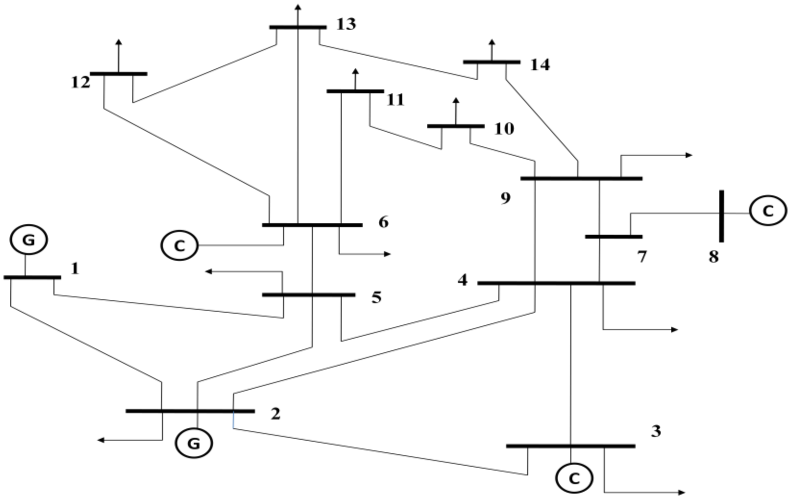


Fig 5. : IEEE 14 bus system

Table 5
Voltage magnitude and phase angle for IEEE 14bus system with and without SVC

	Base Case		SVC at Bus 4		SVC at 14	
	Ploss = 16.0811		Ploss = 13.7587		Ploss = 13.5183	
			Qsvc = 46.4601		Qsvc = 8.4664	
Bus	**|V| (V)**	**δ Degree**	**|V| (V)**	**δ Degree**	**|V| (V)**	**δ Degree**
1	1.060	0	1.060	0	1.0600	0
2	1.045	-5.4778	1.045	-5.0035	1.0450	-4.9682
3	1.0247	-13.682	1.0100	-12.839	1.0263	-12.8400
4	1.0230	-11.464	1.0000	-10.069	1.0261	-10.3534
5	1.0282	-9.8823	1.0132	-8.7109	1.0308	-8.8944
6	1.0564	-16.813	1.0399	-14.797	1.0515	-14.8254
7	1.0379	-15.626	1.0198	-13.376	1.0379	-13.5153
8	1.0771	-15.626	1.0597	-13.376	1.0772	-13.5153

9	1.0233	-17.814	1.0067	-15.103	1.0208	-15.1867
10	1.0156	-18.730	1.0048	-15.349	1.0186	-15.4165
11	1.0317	-17.896	1.0185	-15.200	1.0313	-15.2463
12	1.0411	-17.738	1.0242	-15.702	1.0344	-15.6872
13	1.0356	-17.863	1.0189	-15.777	1.0278	-15.7027
14	1.0180	-19.081	1.0009	-16.678	1.0000	-16.3339

Table 6
Comparison of Results

	Matlab Programming		**Power World Simulator**	
	Power loss (MW)	**Qsvc MVAr**	**Power loss (MW)**	**Qsvc MVAr**
Base case	16.0811	-	15.4	-
SVC at bus 4	13.7587	46.4601	13.1	44.8
SVC at bus 14	13.4279	8.4664	12.7	9

Table 7
Voltage magnitude and phase angle for IEEE 14bus system with and without TCSC

	Base case		**TCSC between line 10-11**		**TCSC between line 12-13**	
Ploss	**16.0811**		**14.3240**		**13.3962**	
Xtcsc			**-0.06**		**-0.06**	
Bus	**|V| (V)**	**Δ Degree**	**|V| (V)**	**δ Degree**	**|V| (V)**	**δ Degree**
1	1.0600	0	1.0600	0	1.0600	0
2	1.0450	-5.477	1.0170	-4.621	1.0450	-4.957
3	1.0247	-13.68	0.9929	-12.932	1.0291	-12.82
4	1.0230	-11.46	0.9895	-10.19	1.0312	-10.40
5	1.0282	-9.88	0.9984	-8.757	1.0354	-8.94
6	1.0564	-16.81	1.0058	-15.49	1.0651	-14.76
7	1.0379	-15.62	0.9720	-13.50	1.0499	-13.5
8	1.0771	-15.62	0.9610	-13.50	1.0887	-13.5
9	1.0233	-17.81	0.9709	-15.27	1.0367	-15.12
10	1.0156	-18.73	0.9759	-15.50	1.0342	-15.34
11	1.0317	-17.89	0.9667	-15.93	1.0459	-15.17
12	1.0411	-17.73	0.9894	-16.42	1.0463	-15.76
13	1.0356	-17.86	0.9839	-16.46	1.0470	-15.65
14	1.0180	-19.08	0.9645	-17.16	1.0309	-16.57

Table 8
Comparison of Results

	Matlab Programming		**Power World Simulator**	
	Power loss (MW)	**Xtcsc**	**Power loss (MW)**	**Xtcsc**
Base case	16.0811	-	15.4	-
TCSC at 10-11	14.3240	-0.06	12.8	-0.05
TCSC at 12-13	13.3962	-0.06	12.9	-0.05

VI. Conclusion

The reactive power control and reduction of transmission loss with realization of SVC and TCSC device is applied to IEEE 9-bus test system and IEEE 14 bus system. The results are compared with MATLAB and Power World Simulator.

The Newton-Raphson power flow solution method which is capable of solving large power network reliably is used to calculate transmission system power loss with flexible AC transmission system (FACTS) devices. The proposed method with FACTS devices are introduced in conventional power flow problem. It considered SVC and TCSC devices in the system to reduced total active power loss.

In 9 bus test system, the SVC device connected to the bus 5 is more effective than the SVC device connected to bus 6 and bus 8 which has reduced power loss to 13.46%. It has also improved the voltage profile of the system.

With TCSC device connected between bus 9 and bus 8, the power loss has reduced to 12.59%. It is more effective than the TCSC device connected between the line 7-8 and 4-6.

This method also applied to the IEEE 14 bus system, the SVC device connected to bus 14 is more effective than the SVC device connected to bus 4 which has reduced power loss to 15.93%. It has also improved the voltage profile of the system.

With TCSC device connected between line 12-13, the power loss has reduced to 16.69%. It is more effective than the TCSC device connected between line 10-11.

The SVC and TCSC device are also used to control the power flow of the system.

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