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Journal of Electrical Systems and Information Technology 5 (2018) 777–793

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Optimal allocation of multi-type FACTS devices and its effect in enhancing system security using BBO, WIPSO & PSO

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Received 19 August 2015; received in revised form 13 December 2016; accepted 10 January 2017
Available online 13 February 2017

Abstract

FACTS devices play a vital role in improving the static as well as dynamic performance of the power systems. However the type, location and rating of the FACTS devices play a major role in deciding the extent to which the objective of improving the system performance is achieved in a cost effective manner. In this work an objective function comprising of cost, line loadings and load voltage deviations is proposed to tap maximum benefits out of their installation and the weights assigned to them decide their relative importance. The impact of installing TCSC, SVC, TCSC-SVC and UPFC in minimizing the formulated objective has been analyzed in enhancing security, under increased system loading conditions.

Keywords: FACTS devices; PSO; WIPSO; BBO; Enhance system security; Optimal placement

1. Introduction

Due to the dynamic load pattern and ever increasing load demand, power flows in some of the transmission lines are well above their normal limits while some of the lines are not loaded up to their full capacity. As a result of this uneven load distribution the voltage profile of the system gets deteriorated which poses a threat for the security of the system. Considering economical and technical constraints involved in setting up new generation resources and limitations faced in purchasing right of ways to realize new transmission corridors, it becomes essential to utilize the existing transmission lines in an efficient manner. FACTS controllers are found to be an effective alternative for the complex task of building up new transmission corridors (Manoj and Puttaswamy, 2011).

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Peer review under the responsibility of Electronics Research Institute (ERI).

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https://doi.org/10.1016/j.jesit.2017.01.008

Modulating and reversing the power flow through the transmission lines a fast, accurate and precise manner was made possible through the FACTS (Flexible Alternating Current Transmission System) concept introduced by Hingorani and Gyugyi (1999). FACTS devices are very effective in improving the voltage profile, reducing the line loadings and line losses, providing reactive power support over a wide range of operating voltages and enhancing the stability of the system. They can as well be used with the existing lines in order to enhance their power transfer capability. The power flow through the network can be controlled without modifying the generation and carrying out any switching operations in the network (Singh and David, 2001). In order to achieve maximum benefits through the installation of the FACTS devices, devices of suitable ratings need to be installed at optimal locations (Benabid et al., 2009).

Optimal placement of FACTS devices is vital to tap the maximum advantages in terms of system performance and cost effectiveness (Aghaei et al., 2012). There are several strategies and approaches in the literature, to solve the issue of FACTS optimization problem. Commonly employed approaches to solve the installation of FACTS devices are sensitivity based analysis (Mandala and Gupta, 2010) and optimization and index calculation method (Hamid et al., 2012a,b). Various techniques adopted to solve the FACTS placement problem are categorized into analytical, linear programming and heuristic based procedures (Sirjani et al., 2012). The optimal location of a given number of FACTS devices is an issue of combinatorial investigation and to solve such sort of issues, heuristic based techniques are observed to be powerful (Gerbex et al., 2001) since they are robust and result in acceptable solutions to real problems within a limited computation time (Radu and Besanger, 2006).

Some common heuristic search techniques to decide the optimal location of FACTS devices in the power system, reported in literature are Genetic Algorithm, Simulated Annealing, Immune Algorithm, Particle Swarm Optimization, Differential Evolution, Harmony search algorithm, and Ant Colony algorithm. The work focuses on a new type of heuristic search algorithm, based on the species behaviour – BBO (Biogeography Based Optimization). It is a population based algorithm, which uses the immigration and emigration behaviour of the species based on various natural factors (Simon, 2008). Application of BBO to solve the economic dispatch problem is described in Bhattacharya et al. (2010) where it has been proved that BBO gives a solution which is comparable with evolutionary programming and differential evolution techniques. In this paper, BBO is applied to solve the optimization problem of finding the optimal placement and capacity of multi-type FACTS devices under varying the system load upto 30% from base case. The results obtained using BBO are compared with PSO and WIPSO (Weight Improved PSO) techniques.

2. Problem formulation

2.1. Objective of the optimization

As the cost of the FACTS devices is high, in order to achieve the maximum benefit, the devices are to be installed at the optimal locations. The objective function has three terms; the first term represents the installation cost of the devices, the second and third terms representing the load bus voltage deviations and line loadings respectively. The minimization of the proposed objective function has to lead to a cost effective security oriented device placement.

The objective function is formulated as

$$Min\,F = W_1\,[(C_{FACTS} * S)] + W_2\,[LVD] + W_3\,[LL] \tag{1}$$

where F is the objective function, C_{FACTS} is the cost of FACTS device in US $/KVar, S is the operating range of the FACTS device, LVD is the Load voltage deviation, LL is the Line loading, W_1, W_2 & W_3 are the weight factors.

2.1.1. Cost (C_{FACTS})

The first term of the objective function C_{FACTS}, presents the installation cost of FACTS devices considered and are given by the following equations.

$$C_{TCSC} = 0.0015s^2 - 0.7130s + 153.75 \tag{2}$$

$$C_{SVC} = 0.0003s^2 - 0.3051s + 127.38 \tag{3}$$

$$C_{UPFC} = 0.0003s^2 - 0.2691s + 188.22 \tag{4}$$

C_{TCSC} is the cost of TCSC device in US $/KVar, C_{SVC} is the cost of SVC device in US $/KVar, C_{UPFC} is the cost of UPFC device in US $/KVar.

2.1.2. Load voltage deviation (LVD)

Excessive high or low voltages can lead to an unacceptable service quality and can create voltage instability problems. FACTS devices connected at appropriate locations play a leading role in improving voltage profile thereby avoiding voltage collapse in the power system. The second term considered represents the load voltage deviations in order to prevent the under or over voltages at network buses.

$$LVD = \sum_{m=1}^{nb} \left(\frac{V_{mref} - V_m}{V_{mref}} \right)^n \quad (5)$$

V_m is the voltage magnitude at bus m, V_{mref} is the nominal voltage at bus m & is considered as 1.0 pu., m refers to the load buses, where V_m is less than V_{mref}.

2.1.3. Line loading (LL)

FACTS devices are located in order to remove the overloads and to distribute the load flows uniformly. To achieve this, line loading is considered as the third term in the objective function.

$$LL = \sum_{l=1}^{nl} \left(\frac{S_l}{S_{l\max}} \right)^n \quad (6)$$

S_l is the apparent power in the line l, $S_{l\max}$ is the apparent power rating of line l.

2.2. The optimization variables

The optimization variables considered in this work are

(a) The number of FACTS devices to be installed is taken as the first variable.
(b) The location of these devices is considered as the second variable to be optimized. TCSC is placed in a line, SVC is placed in a load bus and UPFC is connected between a line & a bus.
(c) Type of the device to be installed is considered as the third variable.
(d) The rating of the device is considered as the fourth variable.

Only one FACTS device per line or bus is permitted.

2.3. Modeling of FACTS devices

2.3.1. TCSC modeling

TCSC is a series compensator. It consists of a series compensating capacitor shunted by a thyristor controlled reactor. With TCSC the power flow control can be controlled by increasing or decreasing the overall lines effective series transmission impedance, by adding a inductive or capacitive reactance correspondingly. The TCSC is modeled as a variable reactance as shown in Fig. 1.

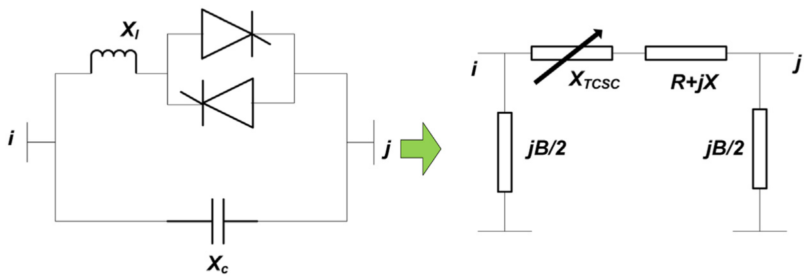

Fig. 1. TCSC modeling.

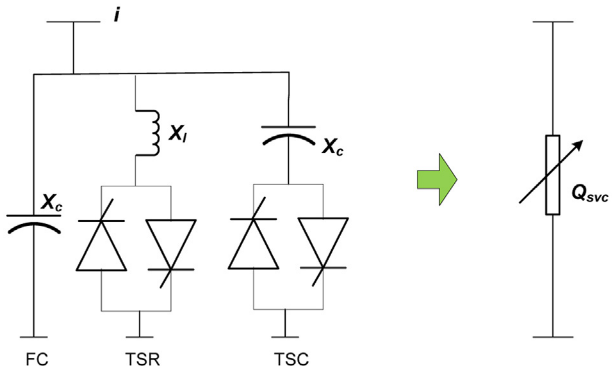

Fig. 2. SVC modeling.

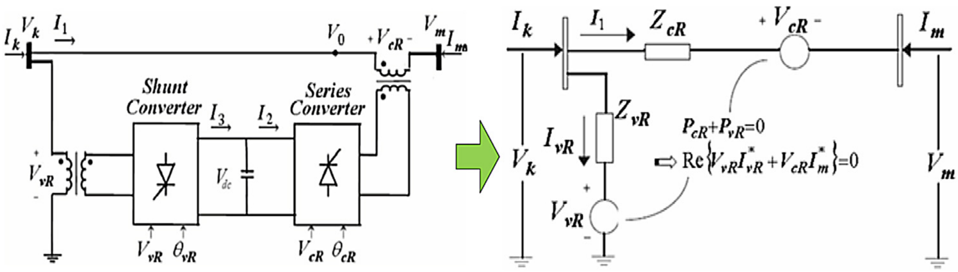

Fig. 3. UPFC modeling.

The working range of TCSC is considered as follows.

$$-0.8X_l \leq X_{TCSC} \leq 0.2X_l \tag{7}$$

X_{TCSC} is the reactance added to the line by placing TCSC. X_l is the reactance of the line where TCSC is located.

2.3.2. SVC modeling

SVC is a shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system. The SVC is a general term for a TCR (thyristor controlled reactor), a TSC (thyristor switched capacitor). It works in two modes, capacitive or inductive mode. In inductive mode, it absorbs reactive power and in capacitive mode, it injects reactive power. It is modeled as an ideal reactive power injection at bus i, where it is connected as depicted in Fig. 2.

The reactive power is limited as follows

$$-100MVAR \leq Q_{SVC} \leq 100MVAR \tag{8}$$

2.3.3. UPFC modeling

UPFC contains a series and a shunt converter connected with the transmission line via coupling transformers. The shunt converter of UPFC can generate or absorb controllable reactive power and provides reactive power compensation. The series converter injects an AC voltage with controllable magnitude and phase angle in series with the transmission line. UPFC is modeled as two ideal voltage sources, one controlled in series and other in shunt between the two buses k and m as shown in Fig. 3.

Series voltage source magnitude, series voltage source angle, shunt voltage source magnitude and shunt voltage source angle are controllable between the limits given by the following equations.

$$V_{CR} = V_{CR\min} \leq V_{CR} \leq V_{CR\max}; V_{CR\min} = \ 0.001 \text{and} V_{CR\max} = \ 0.2(9)$$

$$\theta_{CR} = 0 \leq \ \theta_{CR} \leq 2\pi \tag{10}$$

$$V_{VR} = V_{VR\min} \leq V_{VR} \leq V_{VR\max}; V_{VR\min} = 0.9 \text{and} V_{VR\max} = 1.1 (11)$$

$$\theta_{VR} = 0 \leq \theta_{VR} \leq 2\pi \tag{12}$$

V_{CR} is the series voltage source magnitude, θ_{CR} is the series voltage source phase angle, V_{VR} is the shunt voltage source magnitude, θ_{VR} is the shunt voltage source phase angle

3. Overview soft computing techniques

3.1. PSO technique

Particle swarm optimization is a heuristic search technique developed by Eberhart and Kennedy based on the concept of swarm intelligence exhibited by the flock of birds, school of fish, etc in which each member of the group adjusts its behavior based upon its own experience and the experience of the swarm. This sort of social behavior is used to simulate the problem solving environment in which a swarm is randomly generated in terms of solution variables of the problem. The individuals in a swarm are called particles. After generating the swarm, the fitness values of the particles P_{best} are evaluated and compared against the values obtained from the previous iteration. The particles with the best values of fitness function in the next generation P_{best} are retained. G_{best} is the best value attained so far by the swarm of particles. In each iteration, G_{best} of the current swam is compared with the G_{best} of the previous iteration and whichever is lower is retained along with the corresponding particle.

The position updateof particles is carried out using Eq. (13) in which the velocity is calculated using Eq. (14). The inertia weight in Eq. (14) is calculated using Eq. (15).

$$X_{id}^{k+1} = X_{id}^{k} + V_{id}^{k+1} \tag{13}$$

$$V_{id}^{K+1} = WV_{id}^{K} + c_1 r_1 \left(P_{bestid}^{k} - X_{id}^{k}\right) + c_2 r_2 \left(G_{bestid}^{k} - X_{id}^{k}\right) \tag{14}$$

$$W = W_{\max} - \frac{W_{\max} - W_{\min}}{iter_{\max}} * iter \tag{15}$$

This iterative procedure is repeated till a specified number of swarms are reached or until a predefined amount of time has elapsed or until there is no considerable difference between the outcomes of any two subsequent iterations.

V_{id}^{k+1}-Velocity of the i^{th} individual at $(k+1)^{th}$ iteration.
V_{id}^{k}-Velocity of the i^{th} individual at k^{th} iteration.
X_{id}^{k}-Position of the i^{th} individual at k^{th} iteration.
X_{id}^{k+1}-Position of the i^{th} individual at $(k+1)^{th}$ iteration.
$P_{best\ id}$-Best position of the i^{th} individual.
$G_{best\ id}$-Best position among the individuals.
$r_{1,}\ r_2$-Random numbers distributed within the interval [0,1].
$c_{1,}\ c_2$-Positive constants called acceleration constants.
W-Inertia weight.
$W_{\max}$-Initial value of inertia weight.
$W_{\min}$-Final value of inertia weight.
$iter_{\max}$-Maximum number of iterations.
$iter$-Current iteration number.
$d = 1, 2, ...D$, D is the number of members in a particle.
$i = 1, 2, ...m$, m is the size of the swarm.

3.2. WIPSO technique

WIPSO is based on the improved weight parameter function. For getting the better global solution, the traditional PSO algorithm is improved by adjusting the inertia weight, cognitive and social factors.

The velocity of an individual i of WIPSO is given by

$$V_{id}^{K+1} = W_{new} V_{id}^{K} + c_1 r_1 \left(P_{best\,id}^{k} - X_{id}^{k}\right) + c_2 r_2 \left(G_{best\,id}^{k} - X_{id}^{k}\right) \tag{16}$$

where,

$$W = W_{\max} - \frac{W_{\max} - W_{\min}}{iter_{\max}} \times iter \tag{17}$$

$$W_{new} = W_{\min} + W \times r_3 \tag{18}$$

$$c_1 = c_{1\max} - \frac{c_{1\max} - c_{1\min}}{iter_{\max}} \times iter \tag{19}$$

$$c_2 = c_{2\max} - \frac{c_{2\max} - c_{2\min}}{iter_{\max}} \times iter \tag{20}$$

r_3-Random number distributed within the interval [0,1].
$W_{\max}$-Initial value of inertia weight.
$W_{\min}$-Final value of inertia weight.
$c_{1\min}$-Initial value of cognitive factor.
$c_{1\max}$-Final value of cognitive factor.
$c_{2\min}$-Initial value of social factor.
$c_{2\max}$-Final value of social factor.
$iter_{\max}$-Maximum number of iterations.
$iter$-Current iteration number.

3.3. BBO technique

Biogeography Optimization, an efficient optimization technique was introduced by Simon (2008). BBO algorithm tries to solve the optimization problem through the simulation of immigration and emigration behaviour of the species in and out of a habitat. Species move in and out of the habitats depending upon various factors such as availability of food, temperature prevailing in that habitat, already existing species count in that area, diversity of vegetation, and species in that area etc. and the process strikes a balance when the rate of immigration is equal to the rate of migration. But these behaviours are probabilistic in nature. BBO algorithm exploits the search of the individuals to find them a suitable habitat to probe into the promising regions of the search space. A habitat is defined as an island that is geographically isolated from other areas. A habitat is formed by a set of integers that form a feasible solution for the problem and an ecosystem consists of a number of such habitats. The areas that are well suited as residents for species are said to have high habitat suitability index (HSI). The variable that characterize habitability are called Suitability index variables (SIVs). The large number of species on high HSI islands have many opportunities to emigrate into neighbouring habitats with less number of species. The immigration and emmigration process helps the species in the area with low HSI to gain good features from the species in the area with high HSI and makes the weak elements into strong. Besides it allows retaining good features of species in the area with high HSI. The rate of immigration (λ) and the emigration (μ) are the functions of the number of species in the habitat. Fig. 4 shows the immigration and emigration curves indicating the movements of species in a single habitat. Fig. 4 shows the generalized algorithm for BBO technique.

A set of habitats are generated randomly, satisfying the constraints and their HSI is evaluated. In order to retain elitism, the best habitat having highest HSI is retained without performing migration operation which prevents the best solutions from being corrupted. While the modification operation is performed over the rest of the members, HSI is recalculated for the modified ones thereafter mutation operation is carried out over the extremely good and bad solutions leaving aside the solutions in the middle range. Stopping criteria is similar to any other popular population based algorithm where the algorithm terminates after a pre-defined number of trials or after the elapsing of the stipulated time or where there is no significant change in the solution after several successive trials (Fig. 5).

In BBO, a good solution is referred to an island with high HSI and a poor solution to an island with low HSI. The poor solution in islands with low HSI accept a lot of new features from good solutions in islands with high HSI and

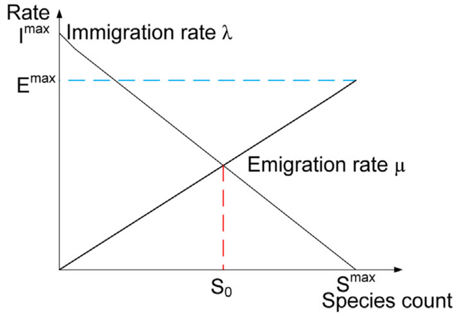

Fig. 4. Species model of single habitat.

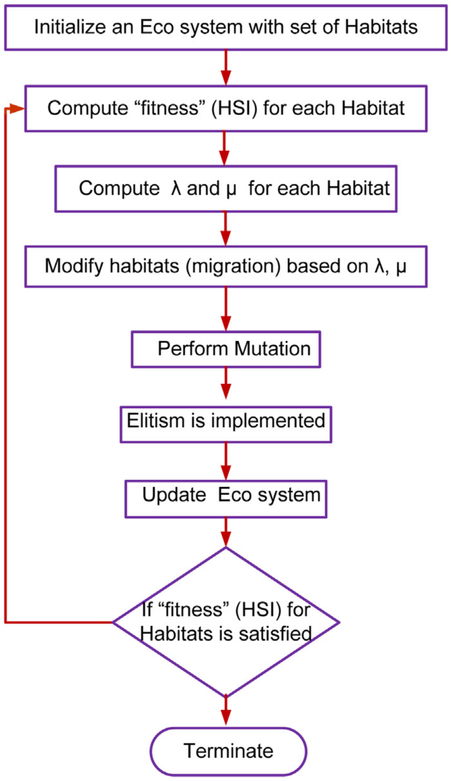

Fig. 5. Generalized algorithm for BBO technique.

improve their quality. However the shared features of the good solutions still remain in the high HSI solutions. The concept of immigration is mathematically represented by a probabilistic model, which relates the probability $P^s(t)$ that a habitat contains exactly S species at time t with that of the probability $P^s(t+\Delta t)$ at time $(t+\Delta t)$ as,

$$P^s(t+\Delta t) = P^s(t)(1-\lambda_s\Delta t-\mu_s\Delta t) + P^{s-1}\lambda_{s-1}\Delta t + P^{s+1}\mu_{s+1}\Delta t \tag{21}$$

If time Δt is so small that the probability of more than one immigration or emigration can be ignored then taking the limit of Eq. (21) as $\Delta t \to 0$ gives the following equation,

$$P^s = \begin{cases} -(\lambda_s+\mu_s)P^s + P^{s+1}\mu_{S+1}s = 0 \\ -(\lambda_s+\mu_s)P^s + P^{s+1}\mu_{s+1} + P^{s-1}\lambda_{s-1}1 \le s \le s^{max} \\ -(\lambda_s+\mu_s)P^s + P^{s-1}\lambda_{s-1}s = s^{max} \end{cases} \tag{22}$$

The equation for the emigration rate μ_k and immigration rate λ_k for k-number of species is developed from Fig. 1 as,

$$\mu_k = \frac{E^{max}}{n} \tag{23}$$

$$\lambda_k = I^{max}\left(1 - \frac{k}{n}\right) \tag{24}$$

When $E^{max} = I^{max}$, the migration and emigration rates can be related as,

$$\lambda_k + \mu_k = E^{max} \tag{25}$$

Mutation rate of each set of solution can be calculated in terms of species count probability using the following equation,

$$m\left(s\right) = m^{max}\left(\frac{1 - P^s}{P^{max}}\right) \tag{26}$$

This mutation scheme tends to increase diversity among the population, avoids the dominance of highly probable solutions and provides a chance of improving the low HSI solutions even more than they already have.

4. Algorithm

4.1. The algorithm for the device placement using PSO and WIPSO techniques

Step1: The system data and the load factor are initialized.

Step2: PSO parameters such as the size of swarm m, maximum number of iterations, the number of variables to be optimized, limits of each variables in the particle, C_1 & C_2 values, $W_{\min}$ & $W_{\max}$, D, velocity limits, P_{best} and G_{best}.

In case of WIPSO

1. Initialize C_{1min} & C_{1max}, $C_{2\min}$ & C_{2max}
2. C_{1min} & C_{1max}, $C_{2\min}$ & C_{2max}, are used to calculate the acceleration constants C_1 & C_2 using Eqs. (19) & (20).
3. An improved function of weight parameter W is calculated using the Eqs. (17) & (18).
4. This improvement in the weight factor and acceleration constant, enhances the WIPSO technique when compared to PSO technique.

Step3: An initial population is randomly generated considering the variables to be optimized. [The number of devices, location of the device, type of device, rating of the device]

Step4: For each particle i [i = 1, 2. . .m] in the population, the objective function is evaluated.

Stpe5: The calculated value of each particle is compared with its P_{best} and P_{best} of each particle is updated.

Step6: G_{best} is calculated, then compared with the G_{best} in the previous iteration and it is updated.

Step7: A new population is created by changing the velocity and position of the particle.

Step8: If stopping criterion is satisfied, the best individual is printed, else repeated from step 4.

Step9: The same procedure is repeated for different load factors.

4.2. The algorithm for the device placement using BBO technique

Step1: The system data and the load factor are initialized.

Step2: BBO parameters such as the size of the suitability index variable n, maximum number of iterations, limits of each variable in the habitat are initialized.

Step3: An initial set of solutions is randomly generated considering the variables to be optimized. [The number of devices, location of the device, type of device, rating of the device]

Step4: The immigration rate λ and emigration rate μ are determined for each of the habitats.

Step4: Elite habitats are identified and they are exempted from modification procedure.

Step5: A habitat H_i is selected for modification proportional to its immigration rate λ_i and the source for this modification will be from the habitat H_j proportional to its emigration rate μ_j. This represents the migration phenomena of the species wherein the new habitats are formed through migration.

Step6: The probability of mutation P_i calculated from λ and μ is used to decide the habitat H_i for mutation and its j^{th} SIV is replaced by a randomly generated SIV.

Step7: Already existing set of elite solutions along with those resulting from the migration and mutation operations result in a new ecosystem over which the steps 4–6 are applied until any one of the stopping criteria is reached.

Step9: The same procedure is repeated for different load factors.

5. Simulated results

To validate the proposed technique, the results are simulated using MATLAB codings for standard IEEE 14, 30 and 57 bus systems. The results are presented for four different cases namely, with only TCSC's connected, with only SVC's connected, with combined TCSC–SVC connected and with only UPFC's connected to the system. All the above cases are studied with PSO, WIPSO and BBO techniques. To study the effect of the installation of FACTS devices under overload conditions, the loads on the system were increased in a step by step manner; the real and reactive power loads connected at various load buses were increased keeping the load power factor constant. The obtained results are presented in Tables 1–6. Number of devices considered for 14 bus, 30 bus and 57 bus are 1, 2 & 3 respectively.

5.1. Case 1-IEEE 14 bus system

Tables 1 and 2.

5.2. Case 2-IEEE 30 bus system

Tables 3 and 4

Table 1
Line loading and load voltage deviation vs. load factor.

Load factor	Line loading					Load voltage deviation				
	Without FACTS	With FACTS devices				Without FACTS	With FACTS devices			
		Devices	Techniques				Devices	Techniques		
			PSO	WIPSO	BBO			PSO	WIPSO	BBO
Base	17.5892	TCSC	16.357	16.331	15.946	0.3509	TCSC	0.2884	0.2872	0.2864
		SVC	17.391	17.388	17.373		SVC	0.2731	0.2701	0.2646
		TCSC & SVC	17.108	17.078	16.804		TCSC & SVC	0.2816	0.2795	0.2766
		UPFC	16.057	15.980	15.704		UPFC	0.1537	0.1501	0.1471
10%	19.2093	TCSC	17.709	17.683	17.146	0.3696	TCSC	0.3079	0.3068	0.3062
		SVC	18.031	18.012	17.966		SVC	0.2921	0.2894	0.2815
		TCSC & SVC	17.864	17.565	17.397		TCSC & SVC	0.3049	0.3031	0.3015
		UPFC	17.594	17.319	17.068		UPFC	0.1783	0.1746	0.1708
20%	20.9319	TCSC	18.579	18.499	17.105	0.4075	TCSC	0.3275	0.3270	0.3266
		SVC	20.686	20.640	20.422		SVC	0.307	0.2986	0.2917
		TCSC & SVC	20.588	20.477	19.763		TCSC & SVC	0.3119	0.2995	0.2929
		UPFC	18.479	18.376	17.019		UPFC	0.1891	0.1839	0.1807
30%	22.4464	TCSC	21.099	20.920	21.281	0.4875	TCSC	0.3479	0.3464	0.3445
		SVC	22.365	22.245	22.143		SVC	0.3147	0.3126	0.3102
		TCSC & SVC	21.546	21.345	21.139		TCSC & SVC	0.3285	0.3264	0.3156
		UPFC	20.744	20.418	20.187		UPFC	0.3101	0.2945	0.2852

Table 2
Device ratings.

Load factor	Device ratings						
	Technique	PSO		WIPSO		BBO	
	Devices	Line/bus	Ratings	Line/bus	Ratings	Line/bus	Ratings
Base	TCSC	5	−0.521	19	0.023	6	−0.714
	SVC	11	10.663	11	12.594	13	9.443
	TCSC & SVC	6	−0.098	14	−0.409	4	−0.78
		8	9.65	8	10.608	9	12.303
	UPFC- shunt	9-16	1.022−1.499	9–16	1.027−2.453	9–16	1.022 −1.499
	UPFC- series	9-16	0.051−0.436	9–16	0.045−0.167	9–16	0.051 −0.436
10%	TCSC	9	−0.714	12	0.17	6	−0.682
	SVC	13	13.547	13	14.202	8	12.996
	TCSC & SVC	6	0.096	19	0.085	19	0.052
		8	9.889	13	10.532	12	11.127
	UPFC- shunt	9-16	1.024−2.396	9–16	1.028−2.172	9–16	1.024 −2.396
	UPFC- series	9-16	0.062−0.330	9–16	0.073−0.319	9–16	0.062 −0.330
20%	TCSC	4	0.141	5	0.193	11	0.168
	SVC	13	19.134	8	15.307	13	19.481
	TCSC & SVC	6	0.157	18	0.19	18	0.095
		8	17.892	8	18.864	9	14.594
	UPFC- shunt	7-15	1.026−2.308	9–16	1.030−2.917	7–15	1.026 −2.308
	UPFC- series	7-15	0.112−1.494	9–16	0.115−1.214	7–15	0.112 −1.494
30%	TCSC	4	0.182	5	0.16	19	0.188
	SVC	13	21.888	13	22.549	11	21.122
	TCSC & SVC	13	0.199	19	0.19	4	0.099
		8	16.768	13	19.381	9	22.673
	UPFC- shunt	7-15	1.010−2.262	7–15	1.032−2.447	7–15	1.010 −2.262
	UPFC- series	7-15	0.110−0.588	7–15	0.117−1.453	7–15	0.110 −0.588

5.3. *Case 3-IEEE 57 bus system*

Tables 5 and 6,Figs. 6–11 .

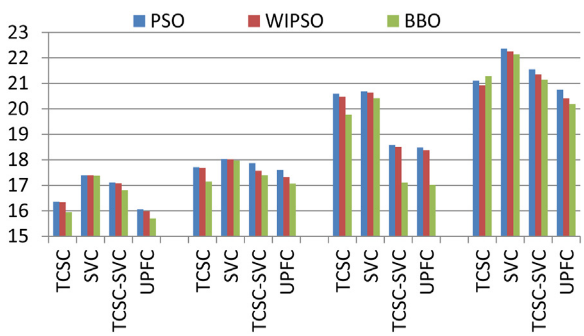

Fig. 6. Load factor vs. line loading for 14 bus system.

Table 3
Line loading and load voltage deviation vs. load factor.

Load factor	Line loading					Load voltage deviation				
	Without FACTS	With FACTS devices				Without FACTS	With FACTS devices			
		Devices	Techniques				Devices	Techniques		
			PSO	WIPSO	BBO			PSO	WIPSO	BBO
Base	14.5592	TCSC	14.212	14.154	14.140	0.6967	TCSC	0.6874	0.6867	0.6849
		SVC	14.460	14.460	14.359		SVC	0.6751	0.6740	0.6733
		TCSC & SVC	14.245	14.159	14.018		TCSC & SVC	0.6764	0.6751	0.6745
		UPFC	14.122	13.923	13.507		UPFC	0.6375	0.6292	0.6117
10%	16.2116	TCSC	15.803	15.306	14.990	0.6974	TCSC	0.6784	0.6772	0.6723
		SVC	16.202	16.177	16.102		SVC	0.6742	0.6733	0.6687
		TCSC & SVC	16.055	15.835	15.522		TCSC & SVC	0.6770	0.6767	0.6706
		UPFC	15.775	15.099	14.815		UPFC	0.6586	0.6515	0.6467
20%	17.9504	TCSC	16.917	16.776	16.551	0.7145	TCSC	0.6881	0.6871	0.6821
		SVC	17.467	17.261	17.058		SVC	0.6840	0.6821	0.6809
		TCSC & SVC	17.071	16.848	16.749		TCSC & SVC	0.6860	0.6836	0.6810
		UPFC	16.807	16.618	16.502		UPFC	0.6752	0.6696	0.6501
30%	19.7258	TCSC	18.195	18.063	17.843	0.7342	TCSC	0.7240	0.7210	0.7185
		SVC	19.441	19.357	19.197		SVC	0.7194	0.7167	0.7149
		TCSC & SVC	18.563	18.223	18.088		TCSC & SVC	0.7203	0.7180	0.7160
		UPFC	18.010	17.902	17.724		UPFC	0.6837	0.6781	0.6574

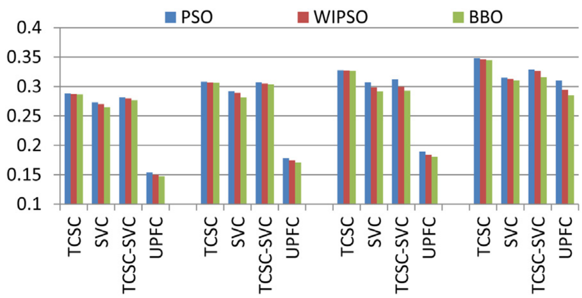

Fig. 7. Load factor vs. load voltage deviation for 14 bus system.

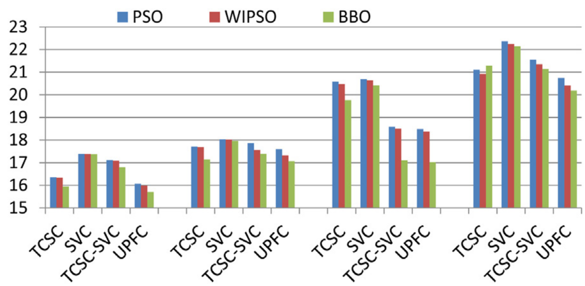

Fig. 8. Load factor vs. line loading for 30 bus system.

Tables 1, 3 and 5 compares the load bus voltage deviations and line loadings under various loading conditions for without FACTS devices and with FACTS devices obtained using PSO, WIPSO and BBO techniques. Tables 2, 4 and 6 give the device placement details and the device ratings of TCSC, SVC, combined TCSC-SVC and UPFC for 14, 30 and 57 bus systems respectively. To visualize the effect of placement of various FACTS devices, bar charts are drawn as shown in Figs. 6–11. This pictorial representation through bar charts clearly depicts the variation of system performance in terms of line loading and load voltage deviation, after FACTS devices using BBO, WIPSO and PSO techniques. Also it reveals the effect of TCSC, SVC, combined TCSC-SVC and UPFC placement under varying loading conditions.

Figs. 6, 8 & 10 demonstrate the impact of placement of FACTS devices in Line Loading of the IEEE-14, IEEE-30 and IEEE-57 bus systems for up to 30% increase in load using PSO, WIPSO & BBO techniques. The figures clearly depict the impact of line loading with the optimal placement of various FACTS devices. The FACTS device placement significantly minimizes the line loading when compared with line loading without FACTS devices. This shows that the system is improved after the placement of FACTS devices. Optimal placement of UPFC minimizes the overall line loading and gives excellent security enhancement when compared with other FACTS devices. Likewise the optimal placement of TCSC gives relatively good performance comparable with UPFC in minimizing line loading.

Figs. 7, 9 & 11 show the effect of placement of FACTS devices in load voltage deviation of the IEEE-14, IEEE-30 and IEEE-57 bus systems with varying the system load up to 30% increase in load using PSO, WIPSO & BBO techniques. The figures reveal that load voltage profile improves significantly with the optimal placement of various

Table 4
Device ratings.

Load factor	Device ratings						
	Technique	PSO		WIPSO		BBO	
	Devices	Line/bus	Ratings	Line/bus	Ratings	Line/bus	Ratings
Base	TCSC	9	−0.005	37	−0.005	10	−0.278
		21	−0.038	8	0.085	15	0.018
	SVC	22	13.937	29	15.261	15	26.202
		23	19.159	18	13.408	20	−6.359
	TCSC & SVC	29	−0.517	37	−0.546	39	−0.357
		26	15.691	28	15.525	15	13.717
	UPFC1-shunt	27–37	1.006	29–39	0.999	24–33	1.004
	UPFC1-series		−1.210		−1.144		−1.116
	UPFC2-shunt						
	UPFC2-series						
		27–37	0.020	29–39	0.134	24–33	0.071
			−1.289		−0.457		−0.051
		24–33	0.999	24–33	1.009	29–39	1.003
			−1.647		−1.713		−1.293
		24–33	0.115	24–33	0.044	29–39	0.016
			−0.156		−0.148		−0.774
10%	TCSC	38	−0.051	39	−0.096	9	0.198
		19	0.110	8	0.164	15	−0.698
	SVC	23	17.281	17	15.853	18	11.620
		25	21.670	20	13.066	19	15.164
	TCSC & SVC	36	0.007	10	−0.104	37	−0.097
		14	9.562	26	10.601	13	11.148
	UPFC1-shunt	25–34	1.006	25–35	0.994	25–34	0.987
	UPFC1-series		−1.154		−1.305		−1.382
	UPFC2-shunt						
	UPFC2-series						
		25–34	0.119	25–35	0.105	25–34	0.019
			−0.513		−0.021		−0.513
		24–33	1.002	24–33	1.009	24–33	1.006
			−1.043		−1.279		−1.280
		24–33	0.028	24–33	0.142	24–33	0.121
			−0.091		−0.526		−0.528
20%	TCSC	37	−0.167	39	−0.166	21	−0.161
		19	0.117	8	0.183	32	−0.147
	SVC	23	16.284	20	7.465	16	32.659
		25	26.049	28	26.070	19	−4.069
	TCSC & SVC	39	−0.750	37	−0.170	37	0.084
		16	31.336	28	40.066	13	34.412

Table 4 (*Continued*)

Load factor	Device ratings						
	Technique	PSO		WIPSO		BBO	
	Devices	Line/bus	Ratings	Line/bus	Ratings	Line/bus	Ratings
	UPFC1-shunt	24–33	1.007	24–31	1.003	24–33	1.004
	UPFC1-series		−2.172		−2.244		−2.353
	UPFC2-shunt						
	UPFC2-series						
		24–33	0.070	24–31	0.014	24–33	0.091
			−0.148		−0.132		−0.184
		25–35	1.002	27–37	1.000	29–39	1.007
			−2.998		−2.281		−2.119
		25–35	0.095	27–37	0.163	29–39	0.119
			−0.601		−0.564		−0.940
30%	TCSC	39	−0.220	10	−0.201	9	0.185
		21	0.187	8	0.048	15	−0.191
	SVC	17	22.996	28	21.780	15	25.463
		24	31.213	20	10.103	20	7.257
	TCSC & SVC	36	−0.040	39	−0.281	37	−0.236
		14	30.281	15	32.426	13	33.708
	UPFC1-shunt	24–33	1.010	25–35	1.003	24–33	1.003
	UPFC1-series		−2.264		−2.969		−2.238
	UPFC2-shunt						
	UPFC2-series						
		24–33	0.126	25–35	0.075	24–33	0.073
			−0.360		−0.315		−0.346
		27–37	1.000	24–33	1.002	25–35	1.006
			−2.227		−2.307		−2.045
		27–37	0.025	24–33	0.115	25–35	0.104
			−1.739		−0.024		−0.721

Table 5
Line loading and load voltage deviation vs. load factor.

Load factor	Line loading					Load voltage deviation				
	Without FACTS	With FACTS devices				Without FACTS	With FACTS devices			
		Devices	Techniques				Devices	Techniques		
			PSO	WIPSO	BBO			PSO	WIPSO	BBO
Base	53.33	TCSC	52.977	52.768	51.956	3.98	TCSC	3.8933	3.8406	3.8393
		SVC	53.260	53.173	52.942		SVC	3.7900	3.7312	3.5499
		TCSC & SVC	52.333	51.361	51.160		TCSC & SVC	3.8610	3.8250	3.7272
		UPFC	50.666	49.761	48.371		UPFC	3.7148	3.6845	3.5125
10%	61.29	TCSC	59.081	58.783	58.185	4.16	TCSC	4.1124	4.1050	4.1024
		SVC	61.161	61.156	60.610		SVC	3.9145	3.7267	3.6508
		TCSC & SVC	59.476	59.240	59.143		TCSC & SVC	4.0647	3.9309	3.7732
		UPFC	57.921	56.579	55.465		UPFC	3.7407	3.6531	3.5041
20%	70.01	TCSC	68.162	68.147	68.138	4.46	TCSC	4.4526	4.3226	4.2605
		SVC	69.920	69.817	69.468		SVC	4.2776	4.1011	4.0732
		TCSC & SVC	68.589	68.296	68.178		TCSC & SVC	4.259	4.113	4.0969
		UPFC	67.191	66.246	65.877		UPFC	4.0939	3.9019	3.8133
30%	79.86	TCSC	77.798	77.572	77.360	4.46	TCSC	4.3703	4.3389	4.2762
		SVC	79.660	79.560	79.107		SVC	4.1416	4.0415	3.9881
		TCSC & SVC	78.862	78.465	77.916		TCSC & SVC	4.3743	4.2923	4.1927
		UPFC	77.060	76.895	74.640		UPFC	4.1019	3.9765	3.9464

FACTS devices. This shows the enhancement of system security under the abnormal loading conditions after the placement of FACTS devices. Even though all the devices improve the profile voltage, the performance of UPFC is highly efficient as in minimizing the line loading. Further analysis shows next to UPFC, SVC also plays its role in improving the voltage profile.

Table 6
Device ratings.

Load factor	Device ratings						
	Technique	PSO		WIPSO		BBO	
	Devices	Line/bus	Ratings	Line/bus	Ratings	Line/bus	Ratings
Base	TCSC	49	0.197	35	−0.217	27	−0.681
		77	−0.231	38	−0.064	35	−0.256
		78	0.001	62	−0.008	45	−0.482
	SVC	16	10.914	29	11.517	53	10.811
		26	11.021	47	12.461	47	13.011
	TCSC & SVC	73	−0.286	56	−0.466	46	−0.609
		74	−0.652	61	−0.305	54	−0.372
		13	24.874	16	23. 412	36	29.573
	UPFC1-shunt	11–24	0.994	29–40	0.886	11–24	0.932
			−1.279		−1.427		−1.774
	UPFC1-series	11–24	0.038	29–40	0.010	11–24	0.032
			−1.112		1.210		1.343
	UPFC2-shunt	31–44	1.013	11–24	0.881	51–64	0.905
			−2.524		−1.482		−1.445
	UPFC2-series	31–44	0.103	11–24	0.036	51–64	0.106
			1.078		1.458		1.192
	UPFC3-shunt	29–67	1.014	51–64	1.004	29–40	0.933
			−2.921		−1.212		−1.163
	UPFC3-series	29–67	0.037	51–64	0.135	29–40	0.054
			1.558		1.373		1.025
10%	TCSC	23	−0.668	19	−0.348	14	−0.775
		38	0.142	36	−0.446	75	−0.129
		63	0.156	39	0.139	77	0.037
	SVC	16	46.209	17	44.143	32	45.514
		26	3.395	30	5.573	40	4.814
	TCSC & SVC	73	−0.251	21	0.118	19	−0.261
		74	−0.113	78	−0.278	64	−0.518
		13	30.638	16	21. 845	41	35.192
	UPFC1-shunt	11–24	1.014	54–70	1.007	54–70	1.007
			−2.875		−2.990		−2.968
	UPFC1-series	11–24	0.116	54–70	0.082	54–70	0.082
			−0.448		1.287		1.312
	UPFC2-shunt	54–70	1.002	31–44	0.995	31–44	0.965
			−2.425		−1.552		−1.008
	UPFC2-series	54–70	0.025	31–44	0.097	31–44	0.127
			1.036		−1.834		−1.826
	UPFC3-shunt	29–41	0.930	29–67	0.969	11–24	1.014
			−1.005		−1.065		−2.781
	UPFC3-series	29–41	0.125	29–67	0.140	11–24	0.033
			1.943		−1.338		1.558
20%	TCSC	14	0.145	56	0.152	18	0.050
		75	−0.119	61	−0.020	73	−0.517
		77	0.179	79	−0.462	74	−0.118

Table 6 (*Continued*)

Load factor	Device ratings						
	Technique	PSO		WIPSO		BBO	
	Devices	Line/bus	Ratings	Line/bus	Ratings	Line/bus	Ratings
	SVC	18	33.623	13	34.614	29	35.816
		34	11.909	29	12.184	53	13.613
	TCSC & SVC	21	−0.507	16	−0.011	45	−0.390
		45	0.103	42	−0.641	79	0.680
		29	34.107	34	29.107	46	37.973
	UPFC1-shunt	54–70	1.014	11–24	0.877	29–40	0.891
			−1.663		−1.525		−1.942
	UPFC1-series	54–70	0.056	11–24	0.059	29–40	0.113
			−0.433		1.945		1.515
	UPFC2-shunt	29–40	0.955	29–40	1.031	11–24	0.952
			−2.163		−2.703		−1.526
	UPFC2-series	29–40	0.138	29–40	0.103	11–24	0.016
			0.607		1.504		−1.103
	UPFC3-shunt	11–24	1.051	54–70	1.013	51–64	1.033
			−2.713		−2.473		−2.106
	UPFC3-series	11–24	0.086	54–70	0.117	51–64	0.094
			−1.321		−1.286		−0.848
30%	TCSC	23	−0.011	47	−0.497	18	−0.657
		38	−0.663	59	−0.734	73	−0.050
		63	0.165	70	−0.293	74	−0.071
	SVC	48	39.480	32	36.477	19	37.271
		50	18.113	40	21.945	38	20.862
	TCSC & SVC	73	0.025	16	−0.057	33	0.177
		74	−0.667	42	−0.776	35	−0.675
		13	39.513	18	36. 137	36	37.545
	UPFC1-shunt	54–70	1.051	29–40	1.022	49–62	0.974
			−2.052		−2.971		−2.613
	UPFC1-series	54–70	0.112	29–40	0.032	49–62	0.101
			−1.382		−0.733		1.319
	UPFC2-shunt	29–67	0.990	51–64	0.971	29–40	1.030
			−2.869		−2.500		−2.091
	UPFC2-series	29–67	0.040	51–64	0.086	29–40	0.032
			1.182		−0.173		−0.751
	UPFC3-shunt	31–44	1.015	11–24	1.021	51–64	1.103
			−1.091		−2.507		−2.444
	UPFC3-series	31–44	0.121	11–24	0.130	51–64	0.111
			−1.231		−0.461		−1.266

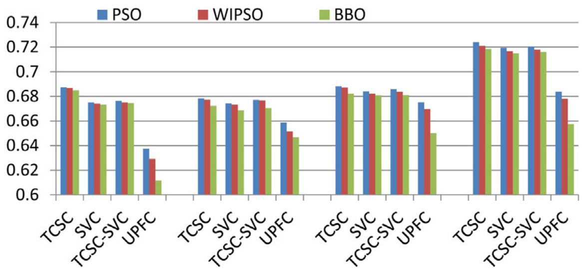

Fig. 9. Load factor vs. load voltage deviation for 30 bus system.

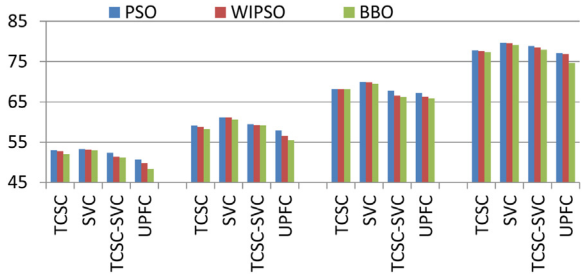

Fig. 10. Load factor vs. line loading for 57 bus system.

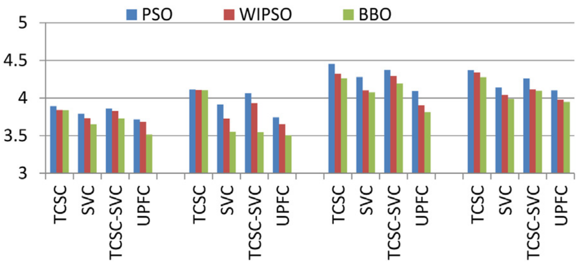

Fig. 11. Load factor vs. load voltage deviation for 57 bus system.

6. Conclusion

The study of FACTS device placement is inevitable, because the maximum capability of power systems can be exploited by means of installing FACTS devices. Though FACTS devices can be placed at any feasible location in the power system, their location and rating have to be fixed optimally to attain the maximum benefit. Here the problem of FACTS devices placement; with comprehensive objective function consisting of cost of the FACTS devices, load voltage deviations and line loadings are analyzed using PSO, WIPSO and BBO algorithms, and the obtained results are compared.

This work investigates and proposes new solution techniques for the optimal placement of FACTS devices, for the enhancement of system security under varying system load. The effectiveness of the optimal installation of TCSC, SVC, combined TCSC-SVC and UPFC in upgrading the security of power systems, in terms of minimizing the line loading and load voltage deviations are examined. The developed algorithms for the optimal placement of various FACTS devices is validated by conducting case studies on standard IEEE test systems. The study shows after the optimal FACTS device placement, both the load bus voltage deviations and line loadings are minimized hence enhancing the system security. Further analysis reveals that BBO technique shows best performance contrasted with PSO and WIPSO strategies. Henceforth the proposed technique based on BBO optimization, yields an efficient solution which considerably reduces load voltage deviations and relieves the lines off their over loads under various loading conditions.

The results acquired clearly depict and hence conclude that

1. The optimal TCSC installation effectively minimizes the line loading when compared to other FACTS devices.
2. The installation of SVC in optimal location, exceptionally enhances the voltage profile when compared to other FACTS devices.
3. Optimal UPFC integration gives best performance in minimizing both line loading and load voltage deviation when compared to other FACTS devices.
4. Further analysis signifies that combined TCSC-SVC indicates reasonably good improvement in minimizing both line loading and load voltage deviations which is comparable with UPFC.

Another important practical issue which has to be considered in the installation of FACTS devices is the cost. UPFC is an expensive device when compared with TCSC and SVC. Indeed, even the installation cost of combined TCSC-SVC will be less when compared to the cost of installing UPFC. In spite of the fact that UPFC gives best performance in minimizing line loading and load voltage deviation; it is apt to choose combined TCSC-SVC when the maximum security is required with minimum cost of installation.

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