

FACTS Devices Allocation to Congestion Alleviation Incorporating Voltage Dependence of Loads

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Abstract: This paper presents a novel optimization based methodology to allocate Flexible AC Transmission Systems (FACTS) devices in an attempt to improve the previously mentioned researches in this field. Static voltage stability enhancement, voltage profile improvement, line congestion alleviation, and FACTS devices investment cost reduction, have been considered, simultaneously, as objective functions. Therefore, multi-objective optimization without simplification has been used in this paper to find a logical solution to the allocation problem. The optimizations are carried out on the basis of location, size and type of FACTS devices. Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are utilized to achieve the determined objectives. The problem is formulated according to Sequential Quadratic Programming (SQP) problem in the first stage. This formulation is used to accurately evaluate static security margin with congestion alleviation constraint incorporating voltage dependence of loads in the presence of FACTS devices and estimated annual load profile. The best trade-off between conflicting objectives has been obtained through Genetic Algorithm (GA) based fuzzy multi-objective optimization approach, in the next stage. The IEEE 14-bus test system is selected to validate the allocated devices for all load-voltage characteristics determined by the proposed approach.

Keywords: Congestion Alleviation, FACTS, Fuzzy, Genetic Algorithm, Optimal Location, Voltage Stability.

1 Introduction

These days, high efficiency, maximum reliability, and security in the design and operation of power systems are more important than ever before. The difficulties in constructing new transmission lines due to limits in rights for their paths make it necessary to utilize the maximum capacity of transmission lines. Therefore, it is difficult to provide voltage stability, even in normal conditions [1] and [2]. The fact that the main duty of generation units in deregulated environment is based on the active power generation requirements rather than the reactive power compensation makes the problem more serious. Power system deregulation which is translated into a separation of generation, transmission and distribution has been developed to increase competition between suppliers. As a result, consumers can seek the

best combination of price, reliability and customer service.

It should be noted that the constraints regarding the transmission security should not prevent any generator from operating at peak load demand. In doing so and also to provide fair competition of generators and secure power transfer transactions between distant regions, both the owners of transmission system and operators should properly plan and control the system. Power exchanges in deregulated systems must be under control in order to avoid line overloading, known as congestion [3], on any path and therefore the full capacity of transmission lines may not be used. So, it is significant to get rid of line congestion to be able to use the full capacity of a network in the restructured electricity environment.

Removing line congestion and carrying higher power, close to lines thermal limit, over long distance in a power system without diminished stability and security margin, can be achieved through fast power flow control in a transmission system. Recently, Flexible AC Transmission Systems (FACTS) have been introduced as a well known term for higher

Iranian Journal of Electrical & Electronic Engineering, 2008.

Paper first received 16th December 2007 and in revised form 10th June 2008.

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controllability in power systems. Fast power flow control is the main application of FACTS devices, which can help us to achieve the above objectives. FACTS devices influence the system by switched or controlled shunt compensation, series compensation or phase shift control. These devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. Thyristor-Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are two mainly emerging FACTS devices that flexibly control line impedance and susceptance, respectively.

It is well documented in the literature that the effectiveness of FACTS controllers mainly depends on their locations [4]. According to the characteristics of FACTS devices, various criteria have been considered in the allocation problem. Some of the reported objectives in the literature are: static voltage stability enhancement [5]-[8], violation diminution of the line thermal constraints [9], network loadability enhancement [10], power loss reduction [11], voltage profile improvement [10], fuel cost reduction of power plants using optimal power flow [12], dynamic stability improvement [13], and damping power swings [14]. It should be noted that each of the mentioned objectives improves the power system network operation and reaching these objectives is desirable in all power system networks. But improvement in one objective does not guarantee the same improvement in others. For instance, in order to improve the voltage stability, as considered here, voltage magnitude alone may not be a reliable indication of how far an operating point is from the collapse point [2]. Hence, satisfying the voltage magnitude constraint does not guarantee the satisfaction of the security margin requirement. By proper TCSC and SVC allocation and setting, both the voltage magnitude and Security Margin (SM) may be improved.

It is clear that the unlimited FACTS devices allocation according to one or more objectives without considering their cost and benefits, cannot be logical [10]. Reducing the investment cost of FACTS devices can be achieved through determination of their optimal number.

This investigation attempts to improve the previously mentioned researches in the field of FACTS devices allocation in power systems. This is done by considering static voltage stability enhancement, voltage profile improvement, congestion alleviation, and FACTS devices investment cost reduction, simultaneously. Therefore, multi-objective optimization without simplification has been used in this paper in an attempt to find a logical solution to the allocation problem. One of the necessities of a multi-objective optimization problem is providing a scheme that can simultaneously formulate all the objectives in the form

of a single optimization problem. The optimization problem needs to have the ability to take all the predetermined objective values by the designer. In this paper, an approach based on fuzzy evaluation technique combined with genetic algorithm is used to compromise between contradictory objectives. Despite previous works, and for approaching a practical solution, estimated annual load profile and voltage dependence of loads have been considered for calculation of the objectives. In addition, Sequential Quadratic Programming (SQP) optimization sub-problem is used as a part of overall optimization procedure to assure all load levels that the FACTS devices are installed optimally (from voltage deviation point of view). The utilized FACTS devices are TCSC and SVC.

2 Security Assessment

In order to determine whether or not the power system meets the voltage level and security requirements specified, it is necessary to determine both the voltage magnitudes and the security margins for the operating conditions anticipated. The voltage magnitudes may be determined by solving the load flow equations for the system. To evaluate the security margin, SM, it is necessary to determine the system critical condition (voltage stability limit). Some approximate methods to determine the critical loading condition has been proposed. A comparison of several proposed indices is given in [15]. These indices may not represent accurately the condition of the network close to and at the critical point. In [16] an accurate method is presented to determine the steady state voltage stability limit at any bus in a multi-machine system. The method of [16] is used in this paper with the presence of TCSC and SVC. Formulation will be developed in such a way that line congestion could be relieve through security margin enhancement in a multi-machine power system.

2.1 Voltage Stability Limit

The problem of determining the voltage stability limit of a general multi-machine power network may be formulated as a nonlinear optimization problem:

Maximize [Total MVA Demand] subject to:

- (a) Distribution constraints at load buses
- (b) MVAR and MW limits on generators
- (c) Generator MW participation
- (d) Load-voltage characteristics at load buses
- (e) Constant power factor of MVA demand (optional)
- (f) Limits on controlled voltages and transformer taps

Consider a power system with N buses. Buses 1 to M are load buses; and buses $M+1$ to N are generator buses. The N^{th} bus is the slack bus. In the steady state, the system is described by power flow equations:

$$P_i = \sum_{j=1}^n V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \phi_{ij}) \quad (1)$$

$$Q_i = \sum_{j=1}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \phi_{ij}) \quad i=1, \dots, N-1 \quad (2)$$

where P_i and Q_i are the net real and reactive power entering bus i , V_i / δ_i is the i^{th} bus complex voltage, Y_{ij} / ϕ_{ij} is the $(i,j)^{\text{th}}$ entry of the network bus admittance matrix. The constraint in (a) describes and enforces the pattern or direction of the increase in the MVA demand vector \underline{S}^T :

$$\underline{S}^T = [S_1, S_2, \dots, S_M] \quad (3)$$

and S_i is MVA demand at bus i .

In this method, it is required that the distribution pattern of the MVA demand to be specified. A vector β has been introduced for this purpose. β_i is a per unit value representing the relative increase in the load at bus i with respect to the corresponding system total load increase. A load distribution constraint equation may then be written for bus i :

$$\beta_i \sum_{j \in J_L} S_j - S_i = \beta_i \sum_{j \in J_L} S_j^{\text{initial}} - S_i^{\text{initial}} \quad (4)$$

where, J_L is the set of load buses and S_i^{initial} is the initial specified MVA demand at bus i .

Generator MW participation in (c) and load-voltage characteristic in (d) can then be formulated as:

$$\begin{cases} f_i = \gamma_i P_D - \gamma_i P_D^{\text{initial}} - P_i + P_i^{\text{initial}} = 0 \\ \gamma_i = \gamma_i^0 \quad \text{if} \quad P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}} \\ \gamma_i \leq \gamma_i^0 \quad \text{if} \quad P_i = P_i^{\text{max}} \end{cases} \quad (5)$$

$i = M+1, \dots, N-1$

$$P_{Li} = P_{0i} V_i^{p_i} \quad (6)$$

$$Q_{Li} = Q_{0i} V_i^{q_i} \quad (7)$$

where γ_i is vector of generator participation factors; P_D is total system demand; P_i^{max} and P_i^{min} are the maximum and minimum MW limits of generating unit i ; P_{0i} and Q_{0i} are the prescribed active and reactive loads at rated voltage; p_i and q_i are constant which reflect the load-voltage characteristic at load bus i .

In mathematics, the formulation may be expressed as a non-linearly constrained optimization problem (NCOP). This NCOP is presented with Eqs. (8)-(17). Minimizing the Eq. (8) by satisfying the constraints in Eqs. (9)-(17), the total MVA demand could be maximized.

$$\text{Minimize } -S_T = \left[-\sum_{j \in J_L} S_j(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) \right] \quad (8)$$

S/T

$$\beta_i S_T(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) - S_i(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) = C_i \quad i \in J_L \quad (9)$$

$$Q_i^{\text{min}} \leq Q_i(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) \leq Q_i^{\text{max}} \quad i = M+1, \dots, N-1 \quad (10)$$

$$P_i^{\text{min}} \leq P_i(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) \leq P_i^{\text{max}} \quad i = M+1, \dots, N-1 \quad (11)$$

$$f_i(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) = 0 \quad i = M+1, \dots, N-1 \quad (12)$$

$$\gamma_i \leq \gamma_i^0 \quad i = M+1, \dots, N-1 \quad (13)$$

$$V_i^{\text{min}} \leq V_i \leq V_i^{\text{max}} \quad i \in J_c \quad (14)$$

$$t_i^{\text{min}} \leq t_i \leq t_i^{\text{max}} \quad i = 1, \dots, n_t \quad (15)$$

$$g_i = P_{0i} V_i^{p_i} + \sum_{j=1}^n V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \phi_{ij}) = 0 \quad (16)$$

$$h_i = Q_{0i} V_i^{q_i} + \sum_{j=1}^n V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \phi_{ij}) = 0 \quad (17)$$

$i \in J_L$

J_c is the set of voltage controlled buses; n_t is the number of LTC transformers.

2.2 Congestion Alleviation

Line congestion can be avoided through the above NCOP problem by considering the following additional constraint:

$$P_{l_i}^{\text{min}} \leq P_{l_i}(\underline{V}, \underline{\delta}, \underline{t}, \underline{\gamma}) \leq P_{l_i}^{\text{max}} \quad l_i = l_1, \dots, l_k \quad (18)$$

where l_1, l_2, \dots, l_k are the line numbers.

Solving the NCOP problem in Eqs. (8)-(18), one can improve the security margin whilst the load of the power system increases according to the relative load increase vector β without any line congestion. This

improvement will be achieved by suitable installation of FACTS devices. Modeling and substitution of FACTS equations in NCOP problem will be discussed in Section 3.

2.3 Security Margin

Having determined the system critical state, the security margin SM is defined as:

$$SM = \frac{\sum_{j \in J_L} S_j^{\text{limit}} - \sum_{j \in J_L} S_j^{\text{initial}}}{\sum_{j \in J_L} S_j^{\text{limit}}} \quad (19)$$

where S_j^{limit} is the MVA load of bus j at critical state. For stable initial operating conditions, SM takes the values between 0 and 1; SM equals to zero at the voltage stability limit and this parameter is negative when the network is unable to supply the specified initial MVA demand.

3 Security Equations with Presence of TCSC and SVC

There are two possible characteristics for TCSCs, capacitive and inductive, to increase or decrease the transmission line reactance. These devices can cause increasing the transmission power capacity of lines, static voltage security margin enhancement, voltage profile improvement, and decreasing power loss (power division between parallel lines). SVCs have also capacitive and inductive characteristics and are predominantly utilized to improve and amend voltage in static and dynamic conditions, reduce reactive network power loss, and enhance static voltage security margin.

In order to use TCSCs and SVCs to satisfy the mentioned allocation criteria, the injection power model and variable susceptance model shown, respectively, in Figs. 1 and 2 have been considered.

Fig. 1 shows lumped model of compensated line k , between buses t and f . The injected active and reactive powers to the mentioned buses are as follows [17],

$$P_{inj}^{\text{TCSC}} = G_{ff}'' V_f^2 + (G_{ft}'' \cos \delta_{ft} + B_{ft}'' \sin \delta_{ft}) V_f V_t \quad (20)$$

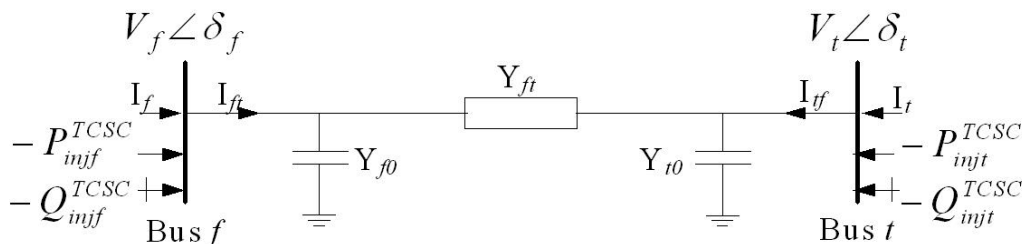


Fig. 1 TCSC injection model.

$$Q_{inj}^{\text{TCSC}} = -B_{ff}'' V_f^2 + (G_{ft}'' \sin \delta_{ft} - B_{ft}'' \cos \delta_{ft}) V_f V_t \quad (21)$$

$$P_{inj}^{\text{TCSC}} = G_{tt}'' V_t^2 + (G_{tf}'' \cos \delta_{tf} + B_{tf}'' \sin \delta_{tf}) V_f V_t \quad (22)$$

$$Q_{inj}^{\text{TCSC}} = -B_{tt}'' V_t^2 + (G_{tf}'' \sin \delta_{tf} - B_{tf}'' \cos \delta_{tf}) V_f V_t \quad (23)$$

where:

$$G_{ft}'' = \frac{X_c R (2X + X_c)}{(R^2 + X^2)(R^2 + (X + X_c)^2)} \quad (24)$$

$$B_{ft}'' = \frac{X_c (R^2 - X(X + X_c))}{(R^2 + X^2)(R^2 + (X + X_c)^2)}$$

Also, $Z (= R + jX)$ is the transmission line impedance, X_c is the magnitude of X_{TCSC} , $\delta_{ft} = \delta_f - \delta_t = -\delta_{tf}$, $Y_{ff}'' = Y_{tt}'' = G_{ff}'' + jB_{ff}'' = -Y_{ft}''$, and $Y_{ft}'' = Y_{tf}'' = G_{ft}'' + jB_{ft}''$.

According to Fig. 2 the drawn current by SVC can be expressed as [18],

$$I_{\text{SVC}} = jB_{\text{SVC}} V_k \quad (25)$$

Reactive power drawn by SVC that is the same as injected power to bus k is written as,

$$Q_{\text{SVC}} = Q_k = -B_{\text{SVC}} V_k^2 \quad (26)$$

Applying the constraints in [16] in the presence of FACTS devices, the additional constraints should be considered for determining the security margin, Eqs. (27) to (30), while t and f belong to J_L . These constraints should be zeroed and they are related to the power balance in load buses in locations where injection power exists. $P_0 V^p$ and $Q_0 V^q$ represent voltage dependency of loads and $p, q \in \{0, 1, 2\}$.

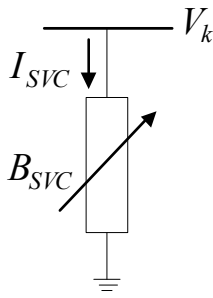


Fig. 2 Variable susceptance of a SVC [18].

Note that the minimum and maximum constraints of TCSC and SVC values should be imposed to determine the security margin. These constraints are presented in Eqs. (31) and (32).

$$g_f = P_{0f} V_f^{Pr} + P_{injf} + \sum_{j=1}^n V_f V_j Y_{fj} \cos(\delta_f - \delta_j - \phi_{fj}) \quad (27)$$

$$g_t = P_{0t} V_t^{Pt} + P_{injt} + \sum_{j=1}^n V_t V_j Y_{tj} \cos(\delta_t - \delta_j - \phi_{tj}) \quad (28)$$

$$h_f = Q_{0f} V_f^{Qf} + Q_{injf} + \sum_{j=1}^n V_f V_j Y_{fj} \sin(\delta_f - \delta_j - \phi_{fj}) \quad (29)$$

$$h_t = Q_{0t} V_t^{Qt} + Q_{injt} + \sum_{j=1}^n V_t V_j Y_{tj} \sin(\delta_t - \delta_j - \phi_{tj}) \quad (30)$$

$[t, f] \in J_L$

$$X_{TCSC_i}^{\min} \leq X_{TCSC_i} \leq X_{TCSC_i}^{\max} \quad i = 1, \dots, n_{TCSC} \quad (31)$$

$$B_{SVC_j}^{\min} \leq B_{SVC_j} \leq B_{SVC_j}^{\max} \quad j = 1, \dots, n_{SVC} \quad (32)$$

4 Problem Formulation and Optimization

4.1 Objective Functions

Here, the aim of optimization is to enhance both voltage magnitude and the security margin of the system. Improving the system security margin includes less congestion as explained in Section 2.2. To meet these aims in an economical manner, the number of TCSC and SVC must be limited to an optimal value. Thus, for a given system, the best compromise must be achieved through a multi-objective optimization.

In mathematics, the objective functions defined by f_1 , f_2 and f_3 , in Eq. (33), are considered.

The objective function f_1 minimizes the investment cost of proposing FACTS devices. It has been assumed that the costs of devices are similar regardless of their capacities. In order to achieve more realistic results in the future work, the cost objective function can be

constituted by active power loss cost and FACTS devices investment cost considers interest rates and capacity of the devices.

$$\left\{ \begin{array}{l} f_1 = N_{facts} \quad f_2 = 1 - SM = \frac{\sum_{j \in J_L} S_j^{initial}}{\sum_{j \in J_L} S_j^{limit}} \\ f_3 = \sum_{i \in J_L} VD_i = \sum_{i \in J_L} \frac{\Phi(|v_i - v_i^{ideal}| - dv_i)}{v_i} \\ \text{and } \Phi(x) = \begin{cases} 0 & \text{if } x < 0 \\ x & \text{otherwise} \end{cases} \end{array} \right. \quad (33)$$

The next objective function is related to the security margin of the system. This objective function depends on the static voltage stability and investigates how the risk of voltage collapse is alleviated. Voltage collapse means a system is unable to provide the load demand and this situation is considered to be a critical state. By knowing this critical state, the system can be secured against voltage collapse. In Eq. (19), SM takes a value between zero and one for a system with normal operating condition. A negative value of SM means the system cannot provide the initial load, and the voltage will definitely collapse. Since minimization is the aim of the optimization rather than maximization, the objective function is rewritten as f_2 in Eq. (33). Furthermore, line congestion can be avoided using the line thermal limit constraint in determination of SM. Therefore, the minimization of objective function f_2 in Eq. (33) causes voltage collapse and line congestion to be avoided.

The third objective function is in regards to the voltage violation of the system. This voltage violation is defined for each bus as f_3 in Eq. (33). In this equation, v_i is the voltage of bus i , v_i^{ideal} is the ideal voltage of bus i (usually equal to 1 pu), and dv_i is the maximum voltage violation tolerance (usually equal to 0.05), SM is the security margin of system and N_{facts} is the number of TCSC and SVC.

4.2 Solution Method for NCOP

The optimization problem NCOP has been solved using the Sequential Quadratic Programming (SQP) algorithm [16], discussed briefly in this section. Without loss of generality, the problem NCOP may be stated as:

$$\begin{array}{ll} \text{Minimize} & G(\underline{Z}) \\ \text{S/T} & \underline{C}(\underline{Z}) = 0 \end{array} \quad (34)$$

The algorithm to solve Eq. (34) generates a sequence of $\underline{Z}^1, \underline{Z}^2, \underline{Z}^3, \dots$ that converges to the solution \underline{Z}^* . Each previous estimate \underline{Z}^k is improved upon by taking a step α^k in a direction $\underline{\Delta Z}^k$ such that $\underline{Z}^{k+1} = \underline{Z}^k + \alpha^k \underline{\Delta Z}^k$. k is the iteration number. The direction of movement, $\underline{\Delta Z}^k$, is found by solving a Quadratic Programming sub-problem defined as:

$$\begin{aligned} \text{Minimize} \quad & G(\underline{Z}^{k+1}) = G(\underline{Z}^k) + \nabla G(\underline{Z}^k) \\ & + \frac{1}{2} \underline{\Delta Z}^{kT} H \underline{\Delta Z}^k \quad (35) \\ \text{S/T} \quad & J \underline{\Delta Z}^k = 0 \end{aligned}$$

where k is the iteration number; H is a positive definite quasi-Newton approximation to the Hessian of the augmented Lagrangian function of the problem (34); J is the Jacobian matrix of the constraint function with respect to \underline{Z}^k ; λ^k is the Lagrange multiplier vector of the constraint function of problem (35). Applying the Kuhn-Tucker theorem to the problem, $\underline{\Delta Z}^k$ and λ^k are found by solving Eq. (36).

$$\begin{bmatrix} H & -A^T \\ A & 0 \end{bmatrix} \begin{bmatrix} \underline{\Delta Z}^k \\ \lambda^k \end{bmatrix} = \begin{bmatrix} \nabla G(\underline{Z}^k) \\ 0 \end{bmatrix} \quad (36)$$

where matrix A is formed from the rows of J .

4.3 Optimization Algorithm

Heuristic methods may be used to solve combinatorial optimization problems. Global optimum solution, the best compromise between conflicting constraints, can be obtained using fuzzy evaluation technique based on genetic algorithm.

4.3.1 Fuzzy Based Multi-Objective Formulation

Fuzzy evaluation technique is a suitable tool for finding the best compromise in multi-objective optimization problems and can be used in both convex and non-convex problems [19]. To achieve trade-off among three competing objectives described in Section

4.1 under different operating conditions and uncertainties, fuzzy evaluation method has been applied to transform the multi-objective optimization into a single objective function (known as the fuzzy performance index). To obtain a single objective function, the objective functions f_1, f_2 and f_3 must be fuzzified first. The membership functions for the number of FACTS devices, security margin and loadability improvement and load bus voltage violations have been displayed in Fig. 3.

In Fig. 3, u_{f_1}, u_{f_2} and u_{f_3} represent the membership values of f_1, f_2 and f_3 . The overall fuzzy performance index is defined as:

$$F = \min(u_{f_1}, u_{f_2}, u_{f_3}) \quad (37)$$

4.3.1 Genetic Algorithm and its Combination with Fuzzy Evaluation Method

A genetic algorithm (GA) is a search technique based on a specific class of evolutionary algorithms. It is capable of solving various kinds of constrained/unconstrained optimization problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear. Standard optimization algorithms such as gradient based methods are not appropriate for such problems. GAs use operators inspired by evolutionary biology such as mutation, natural selection, and crossover. The concept of genetic algorithms is based on a simulation process in which a population of individual solutions is generated and repeatedly modified in order to evolve the optimization problem toward a better solution. Applying selection, crossover and mutation operators to an initial randomly generated population produces a new generation to approach the optimal solution. Due to the probabilistic constitution of a new generation, genetic algorithm based on a random search process is conducted by fitness function of chromosomes (a set of individuals), therefore the search space can be expanded to avoid from being trapped in a local optimum.

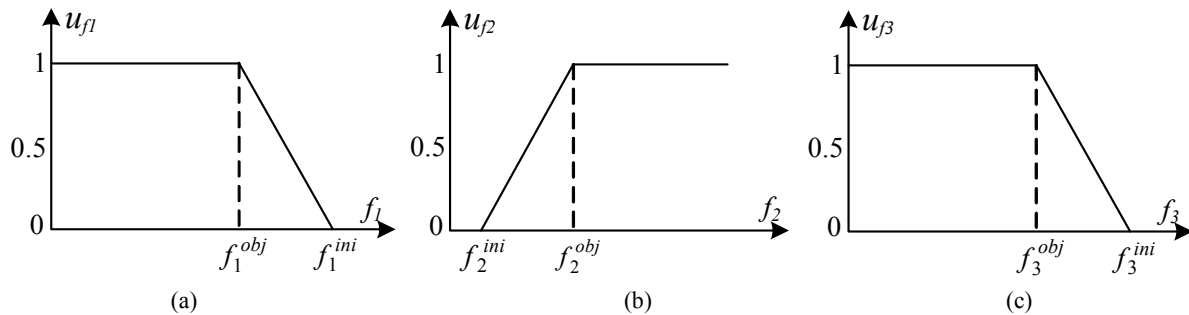


Fig. 3 Fuzzy membership functions for (a) f_1 , (b) f_2 and (c) f_3 . f_i^{ini} and f_i^{obj} represent unaccepted and desired level for each objective function, respectively.

Here, two-point crossover and roulette wheel selection [20] have been utilized to generate the next generation. Each chromosome has been formed from reactance of TCSC candidate lines and susceptance of SVC candidate buses as shown in Fig. 4. In order to prevent fast convergence of the population to a specific value and getting stuck in a local optimum, mutation rate P_m has been used. If the random variable $x_i \in [0,1]$ is greater than P_m the individual in the chromosome remains unchanged, otherwise its value changes in such a way that the assigned individual position between its minimum and maximum is calculated using the

difference between maximum defined position and current position. New calculated position determines new value for the individual between its minimum and maximum. This procedure applies on each individuals.

The genetic algorithm terminates when the maximum number of generations are reached. If the quality of the best member of the population according to the problem objectives is not acceptable, genetic algorithm will be restarted or a fresh search initiated. Fig. 5 illustrates the optimization procedure, a combination of the described GA and fuzzy evaluation method.

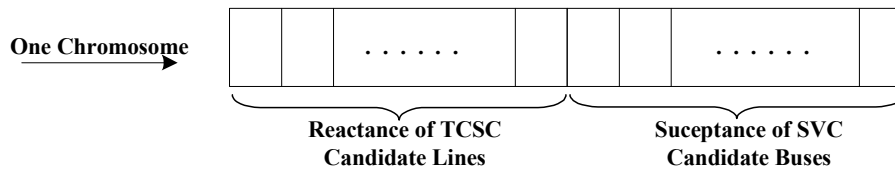


Fig. 4 Formation of one chromosome.

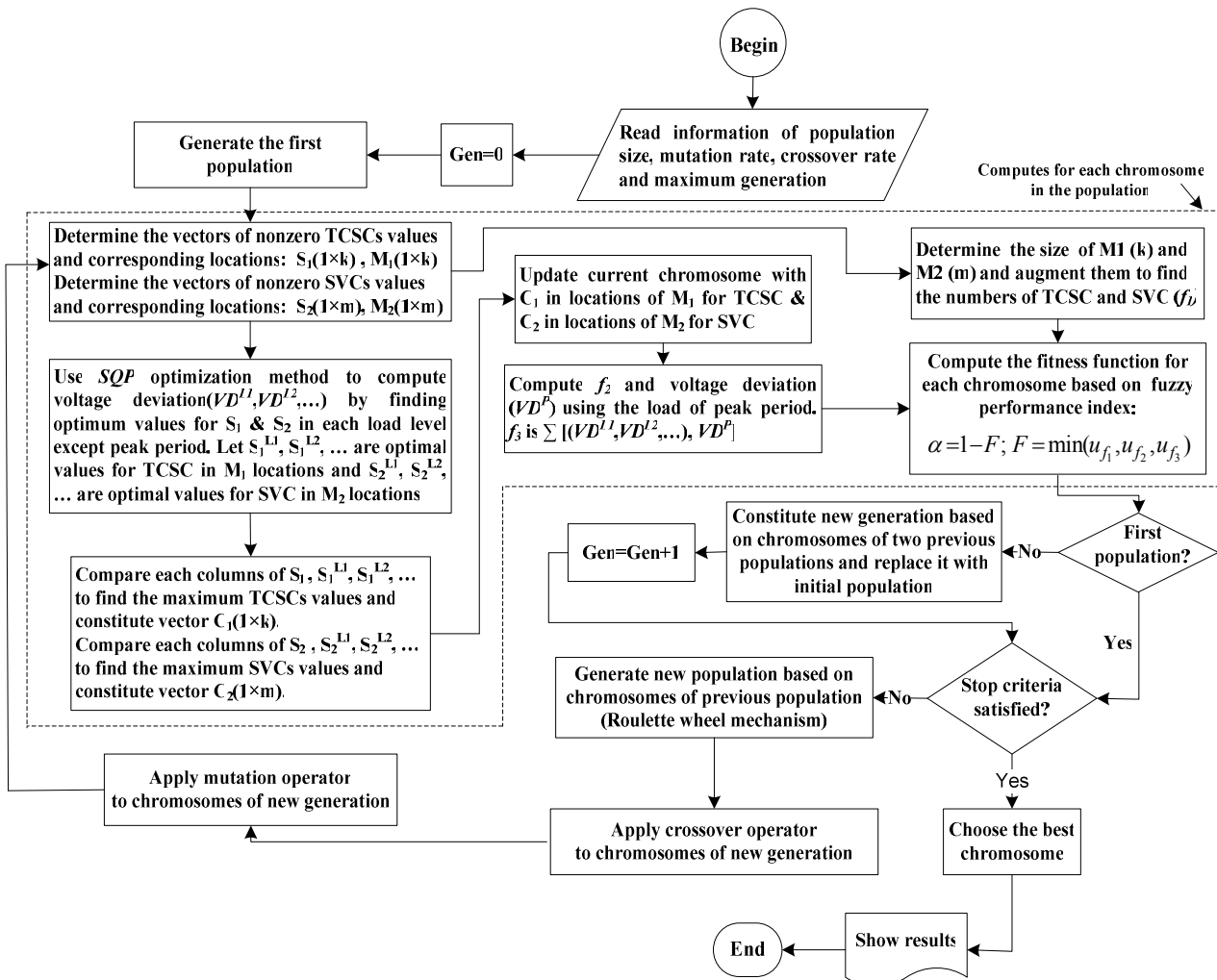


Fig. 5 Combination of genetic algorithm and fuzzy evaluation method in the optimization process.

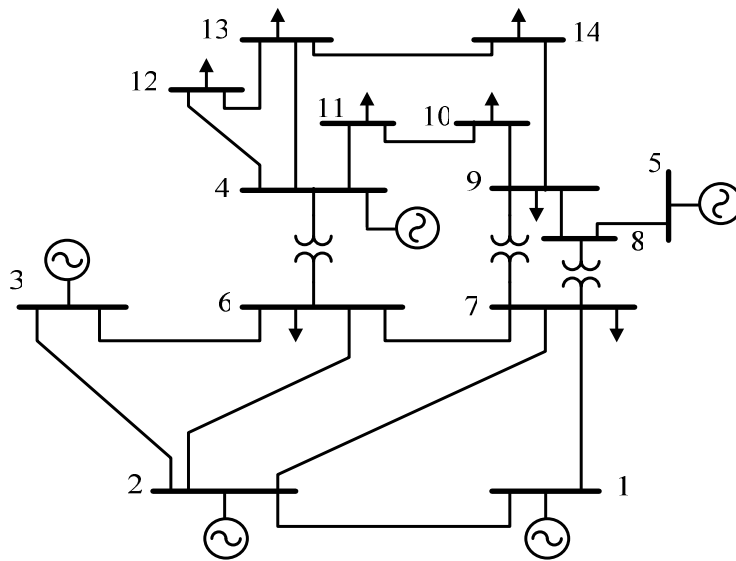


Fig. 6 IEEE 14-bus renumbered test system.

As is clear from Fig. 5, after initialization and randomly generating the first population, the optimization proceeds to find objective functions for each chromosome in the population. In this stage, different load levels are taken into account to consider the estimated annual load profile. It can be helpful to find accurate solutions when the optimization process runs on a practical network. The capacity of TCSC and SVC in nonzero locations of the current chromosome is determined through SQP method to have optimum voltage deviation in each load level. Number of these nonzero locations constitutes the f_1 objective function. The maximum TCSC and SVC capacity of all load levels (except peak period) in each nonzero individual of the current chromosome is used to find f_2 and f_3 objective functions. With the updated TCSC and SVC values, the security margin objective function f_2 computes just for peak load duration. The voltage deviation objective function f_3 is calculated through the sum of each load level optimum voltage deviation and peak load voltage deviation. Computing all objectives, one can find and optimize α using the fuzzy multi-objective technique as follows,

$$\begin{cases} \text{Min } \alpha \\ \alpha = 1 - F ; F = \min(u_{f_1}, u_{f_2}, u_{f_3}) \end{cases} \quad (38)$$

5 Simulation Results

Results obtained by applying the proposed method to the IEEE 14-bus renumbered test system are presented in this section. Fig. 6 shows the single line diagram of the test system. Table 1(a) and 1(b) represent

the initial operating condition and regulated bus data of the network, respectively. Line and transformer data used are taken from [21]. Forecasted load curve which is modeled by three load levels have been used to accurately consider voltage violations. These levels are 0.81, 1 and 0.9 of peak load. Desired and unaccepted levels for objective functions f_1 , f_2 and f_3 have been initialized as $f^{mi} = [10, 0.001, 0.01]$ and $f^{obj} = [3, 0.1, 0.001]$.

Loads are assumed to be independent of bus voltages ($p_i=q_i=0$) and increased uniformly to determine the stability limit. In addition, The effect of voltage dependence of loads is studied by assuming that the static load characteristics may be modeled as in Eqs. (27)-(30). Table 2 represents the system condition at the security limit obtained by the method in [16]. TCSC and SVC were used to improve the security margin and voltage profile of the system. The voltage magnitude limits of regulated buses are set to 1 and 1.1 pu for lower and upper bounds, respectively.

The participation factors of generators are chosen according to their initial MW. It must be mentioned that Eq. (5) is not used to consider re-dispatch. This equation is used for entering the participation of generating units into the SQP optimization procedure during security margin calculations. Therefore, a solution which increases the security margin of the system must satisfy the participation of generating units (as it is usual in determination of the voltage stability limit [22]). This initial participation can be determined based on the initial best dispatch and stored in the vector γ . It means that in estimation of the maximum possible load increase of the network, it is not necessary to add extra economic dispatch constraints of the generating units.

However this assumption may case a little variation in the calculation of the security margin. Increasing of the security margin by proper FACTS installation through satisfying Eq. (18) results in congestion alleviation, too.

In the case of achieving best re-dispatch, an extra cost objective function is needed to calculate the cost of generations after running OPF. In addition, if the best configuration of determined FACTS devices must guarantee the best re-dispatch together with congestion alleviation in the most severe contingencies, another objective function is needed. Compromising between five conflicting objective functions (three objectives have been defined in the paper) is very attractive, however widespread objective space makes the problem very difficult if not impossible. Besides, FACTS devices are incapable of improving all objectives in a power system.

Instead of definition of a new objective function for best re-dispatch, one can define an extra constraint for running OPF to determine the optimal generations in Eq. (5). In this case, two optimization must run together in each iteration of the genetic algorithm. The first one is used for determination of SM and the second is used as a sub-problem for running OPF inside the main algorithm. However, placement of the FACTS devices

for best re-dispatch is a separate problem which researches have been used an independent heuristic approach for this aim [12]. As a result, implementation of the best re-dispatch concept in determination of the security margin with the constraint of line thermal limits is not used in this paper.

The optimization process starts with all lines as initial candidates to locate TCSCs and all PQ buses as initial candidates to locate SVCs. TCSC compensation degree constraints have been assumed to be 70% for TCSC in capacitive mode and 20% in inductive mode [10]. In addition, considering the voltage of 1 pu for all PQ buses, the susceptance of SVC can be changed between 1 and -1 pu in power base of 100 MVA.

The problem solution has been found using genetic algorithm based fuzzy multi-objective optimization method. The parameters of GA i.e. number of generations, size of population and mutation rate are set to 45, 30 and 0.2 respectively. It must be mentioned that the mutation rate is increased adaptively when the possibility of convergence into a local optimum is increased. Furthermore, two-point crossover (crossover fraction is 0.8) and roulette wheel selection [20] have been utilized to generate the next generation.

Table 1(a) Estimation of initial operating condition of the 14-bus renumbered network.

Bus Number	Voltage		Bus Power	
	Mag. (pu)	Ang.	P (MW)	Q (MVAR)
1	1.08	0	0	0
2	1.08	0	157.7	0
3	1.08	0	214.1	0
4	1.08	0	98.0	0
5	1.09	0	0	0
6	1.00	0	167.8	31.6
7	1.00	0	102.9	54.9
8	1.00	0	0	0
9	1.00	0	57.8	16.8
10	1.00	0	19.0	5.80
11	1.00	0	53.5	7.80
12	1.00	0	16.1	6.60
13	1.00	0	27.3	5.80
14	1.00	0	25.4	10.0

Table 1(b) Regulated bus data.

Bus	MVAR Limits		MW Limits	
	Min.	Max.	Min.	Max.
2	-50	100	0	200
3	-50	100	0	300
4	-50	100	0	200
5	-6	40	0	0

Table 2 System condition at voltage stability limit with and without TCSC / SVC ($p_i = q_i = 0$).

Bus No.	Voltage Mag (pu)		Bus Power			
	Without TCSC / SVC	With TCSC / SVC	Without TCSC / SVC		With TCSC / SVC	
			MW	MVAR	MW	MVAR
1	1.08	1.080	32.160	49.24	35.200	44.51
2	1.08	1.080	161.07	81.60	168.04	78.39
3	1.08	1.080	218.68	-10.79	228.13	-16.71
4	1.043	1.061	100.09	100.0	104.42	100.0
5	1.090	1.090	0	24.69	0	15.71
6	0.994	1.000	171.27	32.25	178.65	33.64
7	0.974	0.980	105.03	56.04	109.55	58.45
8	1.050	1.065	0	0	0	0
9	1.013	1.041	59.000	17.15	61.540	17.89
10	0.996	1.038	19.390	5.920	20.230	6.170
11	0.982	1.012	54.610	7.960	56.960	8.300
12	1.006	1.030	16.430	6.740	17.140	7.030
13	1.003	1.024	27.860	5.920	29.060	6.170
14	0.972	0.996	25.930	10.21	27.040	10.65
SM without TCSC/SVC			0.0209			
SM with TCSC/SVC			0.06152			

In Table 3, four TCSCs and one SVC are seen which are the results of optimal allocation of FACTS devices for $p_i=q_i=0$. With this optimal solution for placement of TCSC and SVC, SM improves from 0.0209 to 0.06152. Besides, Table 4 shows that in the absence of allocated TCSC and SVC, lines 4-11 and 4-13 will be overloaded (base loads are taken from Table 1(a)). However, line congestion has successfully been removed for these two lines using TCSC and SVC presented in Table 3. Furthermore, the optimum solution for $p_i = q_i = 0$ is able to remove line congestion in all load-voltage characteristics as indicated in Table 4. In this table, the effect of optimum solution for $p_i = q_i = 0$ on the other load-voltage characteristics have been explored by comparing line powers. As is clear, line congestion has been removed even in different voltage dependency of loads by the aforementioned optimum solution. The effect of load modeling can be analyzed more precisely using the results of Table 5.

As is shown in Table 5, without considering thermal limit of lines, as load exponent increases from zero, the corresponding stability margin increases. It may therefore be said, as stated in [16] and [22], that the constant power representation of loads (loads independent of bus voltage) is the most severe from voltage stability viewpoint. However, this conclusion may not be valid when the thermal limit of lines is

considered. In this case, if there exist some buses that their voltages become greater than 1 pu at the collapse point, increasing the load exponent can result in load increase. If these buses relate to overload lines, higher load exponent will exacerbate the situation from the line congestion point of view. Therefore, the security margin defined in Eq. (19) will be reduced. As an example, Bus 13 in Table 2 has a voltage greater than 1 pu at the stability limit. Using load exponent equal to 2, results in decreasing of SM from 0.0209 to 0.0127 to prevent line 4-13 from more overloading.

In addition, as is shown in Table 5, different optimum solutions will result in different irregular changes in the values of SM when the line thermal limit constraint is considered. However, these changes are small for different optimum structures. The irregular changes are due to different bus voltages in the different structure of the system.

Because the results show that the constant power model is the most severe load representation from voltage stability viewpoint, and different optimum structure results in small changes in the value of SM when the line thermal limit constraint is considered, constant power model has been selected for final decision about the amount, type and location of TCSC and SVC.

Table 3 Optimum solution of TCSC and SVC in different load-voltage characteristics.

Voltage Dependence of Loads	TCSC location		SVC location	Line compensation by TCSC in %	SVC susceptance in pu (capacitive)
	Initial bus	Final bus	Bus number		
$p_i=q_i=0$	2	7	10	-35.45	0.2334
	4	12	-	-61.08	-
	4	13	-	-22.49	-
	13	14	-	9.000	-
$p_i=q_i=1$	1	2	-	-31.57	-
	2	7	-	-35.45	-
	1	7	-	-36.54	-
	9	10	-	-36.98	-
	9	14	-	-46.23	-
$p_i=q_i=2$	2	7	-	-35.44	-
	2	6	-	-35.94	-
	4	12	-	-48.86	-
	10	11	-	-32.54	-
	12	13	-	-31.27	-

TCSC: Negative means capacitive and positive means inductive

Table 4 Comparison of line powers with and without allocated TCSC / SVC in Table 3 for $p_i = q_i = 0$.

Line number	Initial bus	Final bus	Power limits (MW)	Line Active Powers (MW)			
				Without TCSC/SVC	With TCSC/SVC		
					$p_i=q_i=0$	$p_i=q_i=1$	$p_i=q_i=2$
1	2	3	150	100.7	108.5	108.2	107.9
2	3	6	150	111.5	103.4	103.7	104.0
3	1	2	150	39.95	31.50	30.30	29.17
4	2	7	150	109.1	138.7	139.0	139.4
5	2	6	150	108.7	95.65	96.19	96.66
6	1	7	150	71.04	62.50	64.09	65.46
7	6	7	150	9.800	6.050	7.030	7.890
11	4	11	60	62.04	59.42	59.68	59.87
12	4	12	45	20.13	22.90	23.66	24.41
13	4	13	45	46.19	43.03	43.79	44.54
16	9	10	45	14.05	16.20	16.98	17.73
17	9	14	45	5.260	5.520	5.590	5.670
18	10	11	45	5.010	2.940	2.500	2.060
19	12	13	45	3.540	6.220	6.160	6.090
20	13	14	45	21.02	20.69	20.28	19.85

Table 5 Using different load models in determination of the security margin.

	Load model	Security Margin			
		Without TCSC and SVC	With optimum solution for $p_i=q_i=0$	With optimum solution for $p_i=q_i=1$	With optimum solution for $p_i=q_i=2$
With thermal limit of lines	$p_i=q_i=0$	0.0209	0.0615	0.0526	0.0425
	$p_i=q_i=1$	0.0188	0.0617	0.0540	0.0484
	$p_i=q_i=2$	0.0127	0.0595	0.0509	0.0521
Without thermal limit of lines	$p_i=q_i=0$	0.2774	0.3299	0.3263	0.3121
	$p_i=q_i=1$	0.302	0.3459	0.3461	0.3338
	$p_i=q_i=2$	0.3156	0.3571	0.3598	0.3461

Therefore, the optimum solution for $p_i = q_i = 0$ is the best choice for placement of TCSC and SVC in the mentioned system. The evaluation of objective function during optimization process (with the constant power

model for loads) and the enhanced voltage profile of the system during the peak period after using FACTS devices have been shown in Figs. 7 and 8, respectively.

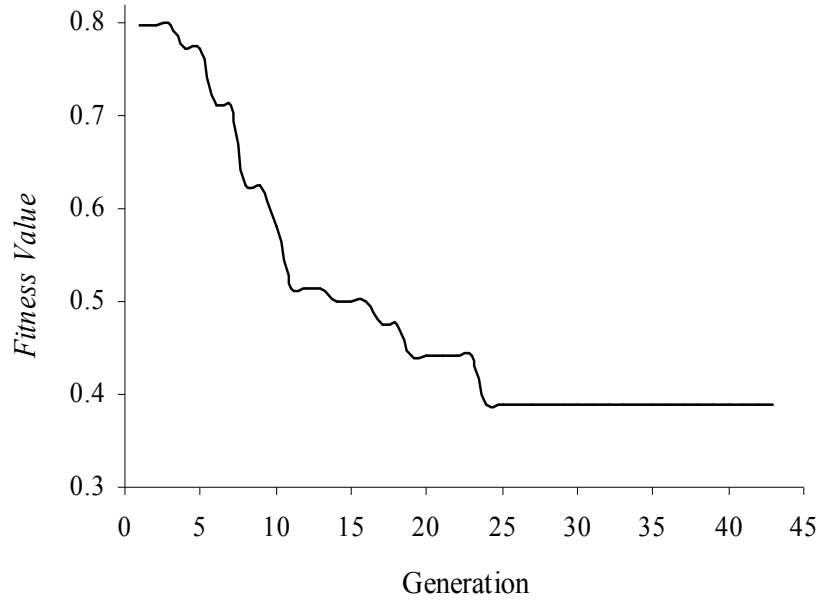


Fig. 7 Objective function evaluation during GA optimization.

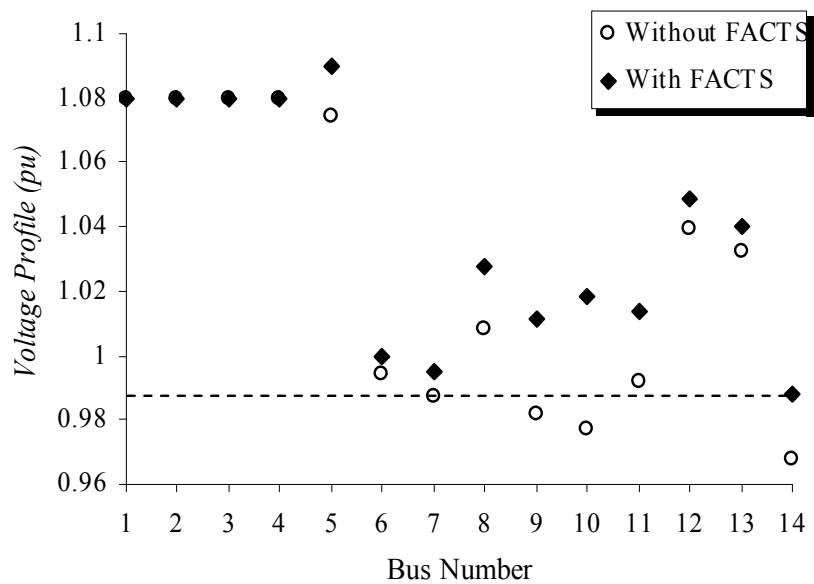


Fig. 8 Voltage profile of IEEE renumbered buses in peak load.

6 Conclusions

In this paper a novel approach has been proposed to determine the optimum amounts, locations, type and number of TCSCs and SVCs based on a multi-objective function.

In this method the allocation problem is investigated with practical considerations. One of these considerations is using the estimated annual load curve, which makes the allocation more accurate. Optimization process utilizes the combination of genetic algorithm, fuzzy method and sequential quadratic programming to find the optimum solution. The optimum allocated devices have been employed as power flow controllers

along system branches or buses in an attempt to enhance both voltage profile and security margin of the system without line congestion.

In contrast to some previous researches, an objective function representing number of the devices is considered along with other objectives to reach an economical solution. However, it has been assumed that the costs of devices are similar regardless of their capacities. In order to achieve more realistic results in the future work, the cost objective function can be constituted by active power loss cost and FACTS devices investment cost considers interest rates and capacity of the devices.

Renumbered IEEE 14-bus test system has been used to validate the performance and effectiveness of the proposed method. Numerical results confirm that the installation of five optimally allocated TCSCs and SVCs can remove the line congestion and improve the security margin with a better voltage profile. Furthermore, results show that the constant power model is the best choice for modeling of the loads. Therefore, optimal structure has been obtained from optimization procedure using constant power model for representation of the loads.

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