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Optimum allocation of FACTS devices in Fars Regional Electric Network using genetic algorithm based goal attainment

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Abstract: This paper presents a novel approach to find optimum locations and capacity of flexible alternating current transmission system (FACTS) devices in a power system using a multi-objective optimization function. Thyristor controlled series compensators (TCSCs) and static var compensators (SVCs) are the utilized FACTS devices. Our objectives are active power loss reduction, newly introduced FACTS devices cost reduction, voltage deviation reduction, and increase on the robustness of the security margin against voltage collapse. The operational and controlling constraints, as well as load constraints, were considered in the optimum allocation. A goal attainment method based on the genetic algorithm (GA) was used to approach the global optimum. The estimated annual load profile was utilized in a sequential quadratic programming (SQP) optimization sub-problem to the optimum siting and sizing of FACTS devices. Fars Regional Electric Network was selected as a practical system to validate the performance and effectiveness of the proposed method. The entire investment of the FACTS devices was paid off and an additional 2.4% savings was made. The cost reduction of peak point power generation implies that power plant expansion can be postponed.

Key words: Flexible alternating current transmission system (FACTS) devices allocation, Multi-objective optimization, Genetic algorithm (GA), Goal attainment

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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 existing transmission lines. Therefore, it is difficult to provide voltage stability, even in normal conditions. The fact that the main duty of generation units is based on the active power generation requirements rather than the reactive power compensation makes the problem more serious.

Flexible alternating current transmission system (FACTS) devices, as modern active and reactive power compensators, can be considered as viable and feasible options for satisfying the voltage security constraints in power systems, since their response to perturbations in urgent circumstances is fast, their performance in normal conditions is flexible, and their operation can fit the dynamic situations.

It is well documented that the effectiveness of FACTS controllers mainly depends on their locations (Okamoto *et al.*, 1995). According to the characteristics of FACTS devices, various criteria have been considered in the allocation problem. Some of the reported objectives are: static voltage stability enhancement (Chang and Huang, 1998; Sharma *et al.*, 2003; Yorino *et al.*, 2003; Song, 2004), violation diminution of the line thermal constraints (Lu and Abur, 2002), network loadability enhancement (Jurado and Rodriguez, 1999; Gerbex *et al.*, 2001), loss reduction (Singh and David, 2000), voltage profile improvement (Gerbex *et al.*, 2001), power plants fuel cost reduction using optimal power flow (Ongsakul and Bhasaputra, 2002), and economical approach that has minimized the overall system cost function (Cai *et al.*, 2004). It should be noted that each of the mentioned objectives improves the power system network operation and that 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, satisfying the voltage magnitude constraint does not result in the satisfaction of the voltage stability requirement (Obadina and Berg, 1988). Also, it is obvious that the minimum power loss leads to power system lines optimum operation, whereas it may exacerbate the static voltage stability limit. Therefore, none of the mentioned technical objectives can be neglected in FACTS devices allocation. On the other hand, allocation of the unlimited FACTS devices due to one or more objectives without considering the cost of the devices cannot be justified despite the assumption in (Gerbex *et al.*, 2001). Therefore, both technical and economical objectives should be involved in the FACTS allocation problem. In previous efforts to approach these objectives, some simplifications have been made such as allocation based on decoupled active and reactive components (Song, 2004), the definition of the cost function without including the interest rate, or active power loss price (Cai *et al.*, 2004). In (Radu and Bésanger, 2006), although a multi-objective genetic algorithm (MOGA) approach has been implemented for FACTS devices allocation, only two objectives with different dimensions, including line overload and voltage violation reduction, have been simplified and augmented to constitute a single objective function. In addition, in economic objective function definition, the interest rate has not been included. These assumptions cause some problems such as the inability to use all achievable advantages of FACTS devices, impractical allocation results, and inaccurate solution to the problem.

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, power loss reduction, and voltage profile improvement as the allocation objectives; FACTS devices investment cost reduction considers interest rates 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. Despite previous works, and for approaching a practical solution, an estimated annual load profile has been considered for calculating power losses and voltage violation. The utilized FACTS devices are thyristor controlled series compensators (TCSCs) and static var compensators (SVCs).

Providing a scheme for simultaneously translating all the objectives into a single optimization problem is one of the necessities in the case of a multi-objective optimization problem. The optimization problem should have the capability of taking all the predetermined objective values by the designer. Here, an approach based on the goal attainment method (Gembicki and Haimes, 1975), combined with a genetic algorithm (GA), is used to compromise between contradictory objectives. In addition, in order to implement the estimated annual load profile for accurately finding the optimum location and capacity of FACTS devices, a sequential quadratic programming (SQP) optimization sub-problem in combination with a goal attainment method has been used as a part of the overall optimization procedure, which is mainly based on the GA. The problem formulation makes it possible to under- or over-achieve the objectives, enabling the designer to be relatively imprecise about the initial design goals. The relative degree of under- or over-achievement of the goals can be controlled by means of the weighting coefficients vector.

This paper is organized as follows. Section 2 is devoted to the mathematical concept of the multi-objective allocation. Section 3 describes the models of the TCSC and the SVC that have been used for static security enhancement. The goal attainment method has briefly been described in Section 4, as well as the introduction of the implemented optimization procedure. The results achieved by applying the proposed method to Fars Regional Electric Network are presented and analysed in Section 5. The locations and rating of the nominated devices that satisfy the mentioned objectives are also determined in this section. Finally, Section 6 concludes the paper.

PROBLEM FORMULATION AND OBJECTIVE FUNCTION

Three objective functions have been considered. The first one is related to the active power loss, investment cost, and peak point power generation. This objective minimizes the active power loss cost, investment cost of proposing FACTS devices, and peak point power generation. It can be expressed as

$$f_1(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z}) = K_\mathrm{e}\sum_i (P_{\mathrm{loss}i}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z})T_i) + K_\mathrm{i}C_\mathrm{inv}(\boldsymbol{z}) + K_\mathrm{p}P_\mathrm{peak}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z}), \quad (1)$$

where $\boldsymbol{u}$ is the control variable vector, $\boldsymbol{x}$ is the state variable vector; $\boldsymbol{z}$ is the vector containing amount and type of FACTS devices; K_e is the active power cost (\$/(kW·h)); K_i and K_p are investment and plant cost factors, respectively; T_i is the time length related to the ith load level (h); $P_{\mathrm{loss}i}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{z})$ is the active power loss of the ith load level from the system annual load curve (kW); $P_\mathrm{peak}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{z})$ is the peak point power generation in year of study (kW). $C_\mathrm{inv}(\boldsymbol{z})$ is defined as follows:

$$C_\mathrm{inv}(\boldsymbol{z}) = \sum_i C_{\mathrm{MV\cdot A\_SVC}i}S_{\mathrm{SVC}i} + \sum_j C_{\mathrm{MV\cdot A\_TCSC}j}\,S_{\mathrm{TCSC}j}, \quad (2)$$

where $S_{\mathrm{SVC}i}$ and $S_{\mathrm{TCSC}j}$ are complex powers of the ith SVC and the jth TCSC, respectively; $C_{\mathrm{MV\cdot A\_SVC}i}$ and $C_{\mathrm{MV\cdot A\_TCSC}j}$ are the cost of 1 MV·A related to the ith SVC and the jth TCSC, respectively, and are determined by (Cai *et al.*, 2004)

$$\begin{cases} C_\mathrm{MV\cdot A\_TCSC} = 1.5S_\mathrm{TCSC}^2 - 713S_\mathrm{TCSC} + 153750, \\ C_\mathrm{MV\cdot A\_SVC} = 0.3S_\mathrm{SVC}^2 - 305S_\mathrm{SVC} + 127380. \end{cases} \quad (3)$$

It is noted that the comparison between power loss cost reduction and devices investment cost should be carried out in the same year as the allocation study. Therefore, after the calculation of power loss according to the load curve of the mentioned year, other costs such as the necessary investment of new devices and benefits from peak point power generation reduction on the basis of interest rate, life time of new devices and power plants are combined into a single objective function. This is carried out using K_p and K_i factors with

$$K_\mathrm{i} = \frac{(1+B)^{n_\mathrm{facts}}\,B}{(1+B)^{n_\mathrm{facts}}-1}, \quad K_\mathrm{p} = A\frac{(1+B)^{n_\mathrm{plant}}\,B}{(1+B)^{n_\mathrm{plant}}-1}, \quad (4)$$

where A is the power plant installation cost (\$/kW); B is the refundable investment rate (%); n_facts and n_plant are the life time of FACTS devices and power plants, respectively (year).

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 that a system cannot 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. The security margin of a system according to the critical state can be expressed as follows (Obadina and Berg, 1988):

$$SM = \left(\sum_{j\in J_L} S_j^\mathrm{lim} - \sum_{j\in J_L} S_j^\mathrm{ini}\right)\Bigg/\sum_{j\in J_L} S_j^\mathrm{lim}, \quad (5)$$

where S_j^ini and S_j^lim are loads (in MV·A) related to load bus j at initial and limit (critical) states, respectively; J_L is a set containing all load buses; SM takes a value between 0 and 1 for a system with normal operating conditions. A negative value of SM means that the system cannot provide the initial load, and the voltage will definitely collapse.

Since minimization rather than maximization is the aim of the optimization, the objective function is rewritten as

$$f_2(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z}) = 1 - SM = \sum_{j\in J_L} S_j^\mathrm{ini}\Big/\sum_{j\in J_L} S_j^\mathrm{lim}. \quad (6)$$

The minimization of this objective function can avoid the voltage collapse.

The third objective function is with respect to the voltage violation of the system. This voltage violation is defined for each bus as follows (Chen and Liu, 1994):

$$VD_i = \frac{\Phi(|v_i - v_i^\mathrm{ideal}| - dv_i)}{v_i}, \quad (7)$$

where

$$\Phi(x) = \begin{cases} 0, & \text{if } x<0, \\ x, & \text{otherwise,} \end{cases}$$

v_i is the voltage of bus i, v_i^ideal (usually equal to 1 p.u.)

is the ideal voltage of bus i, and dv_i is the maximum voltage violation tolerance. Therefore, the third objective function is

$$f_3(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z})=\sum_{i\in J_L}VD_i=\sum_{i\in J_L}\frac{\Phi(|v_i-v_i^{\text{ideal}}|-dv_i)}{v_i}. \quad (8)$$

Minimization of this objective function forces the voltages to remain in the specified range.

In the proposed multi-objective optimization, some constraints such as compromise between active and reactive powers of load buses, a permitted range of active and reactive generating powers of power plants, an allowed tap range of transformers, maximum power transmission of lines, and a permitted range of FACTS devices have been considered. The goal of the problem is to find an optimum configuration, χ^*, among the feasible configurations, χ, through installing new devices or only on the basis of current devices in such a way that all objective forces become optimum and the defined nonlinear constraints are satisfied. The mathematical description can be written as

$$\min_{\boldsymbol{u},\,\boldsymbol{z}\in\chi}\{f_1(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z}),\,f_2(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z}),\,f_3(\boldsymbol{x},\boldsymbol{u},\boldsymbol{z})\}. \quad (9)$$

TCSC AND SVC MODELS: MODIFICATION ON VOLTAGE SECURITY EQUATIONS

There are two possible characteristics for TCSCs, capacitive and inductive, to increase or decrease the transmission line reactance. These devices can cause an increase in the transmission power capacity of lines, static voltage security margin enhancement, voltage profile improvement, and decreasing power loss (power division between parallel lines). SVCs also have capacitive and inductive characteristics and are predominantly utilized to improve and amend voltage in static and dynamic conditions, to reduce reactive network power loss, and to enhance the 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 in Figs.1 and 2, respectively, have been considered. Fig.1 shows a lumped model of compensated line k between buses t and f. The injected active and reactive powers to the mentioned buses are as follows (Padhy and Abdel Moamen, 2005):

$$P_{\text{inj}f}^{\text{TCSC}}=G_{ff}''V_f^2+(G_{ft}''\cos\delta_{ft}+B_{ft}''\sin\delta_{ft})V_fV_t, \quad (10)$$

$$Q_{\text{inj}f}^{\text{TCSC}}=-B_{ff}''V_f^2+(G_{ft}''\sin\delta_{ft}-B_{ft}''\cos\delta_{ft})V_fV_t, \quad (11)$$

$$P_{\text{inj}t}^{\text{TCSC}}=G_{tt}''V_t^2+(G_{tf}''\cos\delta_{tf}+B_{tf}''\sin\delta_{tf})V_fV_t, \quad (12)$$

$$Q_{\text{inj}t}^{\text{TCSC}}=-B_{tt}''V_t^2+(G_{tf}''\sin\delta_{tf}-B_{tf}''\cos\delta_{tf})V_fV_t, \quad (13)$$

where G_{ft}'' and B_{ft}'' are defined as

$$\begin{cases} G_{ft}''=\dfrac{X_{\text{c}}R(2X+X_{\text{c}})}{(R^2+X^2)[R^2+(X+X_{\text{c}})^2]},\\ B_{ft}''=\dfrac{X_{\text{c}}[R^2-X(X+X_{\text{c}})]}{(R^2+X^2)[R^2+(X+X_{\text{c}})^2]}. \end{cases} \quad (14)$$

Also, $Z=R+\text{j}X$ is the transmission line impedance, where R and X are the resistance and reactance (in p.u.) of line, respectively; X_{c} (in p.u.) is the magnitude of X_{TCSC}; and $\delta_{ft}=\delta_f-\delta_t=-\delta_{tf}$, $Y_{ff}''=Y_{tt}''=G_{ff}''+\text{j}B_{ff}''=-Y_{ft}''$, $Y_{ft}''=Y_{tf}''=G_{ft}''+\text{j}B_{ft}''$.

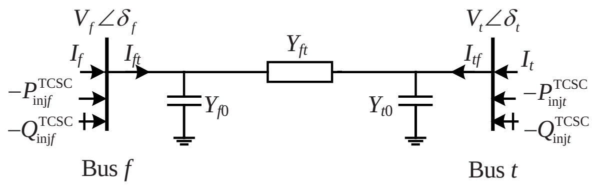

Fig.1 Injection power model of a TCSC

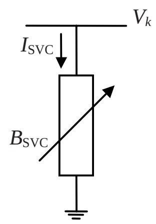

Fig.2 Variable susceptance of an SVC (Ambriz-Perez *et al.*, 2000)

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

$$I_{\text{SVC}}=\text{j}B_{\text{SVC}}V_k. \quad (15)$$

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

$$Q_{\text{SVC}}=Q_k=-B_{\text{SVC}}V_k^2. \quad (16)$$

Also, the following extra constraints are considered for determining the security margin while t and f belong to J_L (Obadina and Berg, 1988):

$$g_f = P_{0f}V_f^{p_f} + P_{\text{inj}f} + \sum_{j=1}^{n} V_f V_j Y_{fj} \cos(\delta_f - \delta_j - \phi_{fj}) = 0, \quad (17)$$

$$g_t = P_{0t}V_t^{p_t} + P_{\text{inj}t} + \sum_{j=1}^{n} V_t V_j Y_{tj} \cos(\delta_t - \delta_j - \phi_{tj}) = 0, \quad (18)$$

$$h_f = Q_{0f}V_f^{q_f} + Q_{\text{inj}f} + \sum_{j=1}^{n} V_f V_j Y_{fj} \sin(\delta_f - \delta_j - \phi_{fj}) = 0, \quad (19)$$

$$h_t = Q_{0t}V_t^{q_t} + Q_{\text{inj}t} + \sum_{j=1}^{n} V_t V_j Y_{tj} \sin(\delta_t - \delta_j - \phi_{tj}) = 0. \quad (20)$$

These constraints are related to the power balance in load buses in locations where injection power exists. p_f, q_f and p_t, q_t are constants that reflect the load-voltage characteristics at buses f and t, respectively. P_0 and Q_0 are prescribed real and reactive loads at rated (normal) voltage (in p.u.), respectively. P_0V^p and Q_0V^q represent the voltage dependency of loads, and $p, q \in \{0, 1, 2\}$.

Note that the minimum and maximum constraints of TCSC and SVC values should be imposed to determine the security margin,

$$X_{\text{TCSC}i}^{\min} \le X_{\text{TCSC}i} \le X_{\text{TCSC}i}^{\max}, \quad i = 1, 2, ..., n_{\text{TCSC}}, \quad (21)$$

$$B_{\text{SVC}j}^{\min} \le B_{\text{SVC}j} \le B_{\text{SVC}j}^{\max}, \quad j = 1, 2, ..., n_{\text{SVC}}, \quad (22)$$

where $X_{\text{TCSC}i}$ is the reactance of the ith TCSC (p.u.) and $B_{\text{SVC}j}$ is the susceptance of the jth SVC (p.u.).

GA BASED GOAL ATTAINMENT

Goal attainment method

The goal attainment method is a powerful tool for finding the best compromise in multi-objective optimization problems and can be used in non-convex as well as convex problems (Gembicki and Haimes, 1975). In this method, we consider a weighted vector $\boldsymbol{w}$, which depends on the direction movement toward the predetermined objectives, and a goal vector $\boldsymbol{y}$ for optimization. To find the best compromise between conflicting objectives, the following problem needs to be solved (Chen and Liu, 1994):

$$\min \alpha \ \text{ s.t. } \ \boldsymbol{y} + \alpha \boldsymbol{w} \ge f(\boldsymbol{k}), \ \ \boldsymbol{w} \in \Lambda_\varepsilon, \ \boldsymbol{k} \in \chi, \quad (23)$$

where α is a scalar variable without any sign limit, χ is the set of feasible solutions, and Λ_ε is defined as

$$\Lambda_\varepsilon = \left\{ \boldsymbol{w} \in \mathbb{R}^m \mid w_i \ge \varepsilon, \ \sum_{i=1}^{m} w_i = 1, \ \varepsilon \ge 0 \right\}. \quad (24)$$

The mechanism of the goal attainment method for a case with two objectives has been depicted in Fig.3.

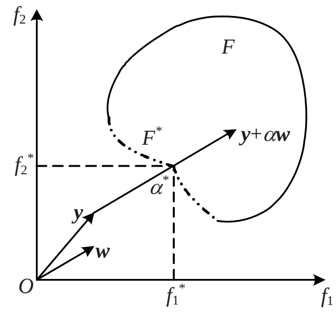

Fig.3 Goal attainment method for a case with two objectives (Chen and Liu, 1994)
F: feasible region in the objective space, F^*: optimum solution region. (f_1^*, f_2^*, α^*) is the optimum solution based on decision's preferences

The goal vector $\boldsymbol{y}$ and direction vector $\boldsymbol{w}$ are obtained from the selected values of the decision maker. The direction of vector $\boldsymbol{y}+\alpha\boldsymbol{w}$ can be obtained by knowing vectors $\boldsymbol{y}$ and $\boldsymbol{w}$. Therefore, Eq.(23) means finding an acceptable point on this vector in the objective space in such a way that the obtained point is the closest point to the origin. It is obvious that the optimum solution of Eq.(23) is a point in which the vector $\boldsymbol{y}+\alpha\boldsymbol{w}$ reaches the solution region F^* in the objective space F.

Optimization approach

A global optimum solution, the best compromise between conflicting constraints, can be obtained using the goal attainment method based on a GA. The GA is a search technique based on a specific class of evolutionary algorithms. It can solve various kinds of constrained/unconstrained optimization problems in which the objective function is discontinuous, non-differentiable, 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 (Goldberg, 1989).

Here, two-point crossover and roulette wheel selection (Goldberg, 1989) have been utilized to generate the next generation. Each chromosome has been formed from the reactance of TCSC candidate lines and the 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, adaptive mutation rate P_m has been used.

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

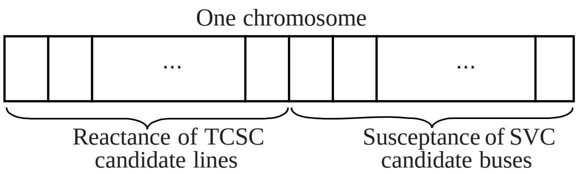

Fig.4 Formation of one chromosome

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. To find the investment cost of TCSC and SVC, their capacities have to be known according to Eq.(2). The capacity of TCSC and SVC in nonzero locations of the current chromosome is determined through an SQP approach (Gill *et al.*, 1981) to have the optimum loss and voltage deviation in each load level. The maximum TCSC and SVC capacity of all load levels in each nonzero individual of the current chromosome, in addition to each level of optimized cost of loss, determines the objective function f_1. 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 the objectives, one can find and optimize α using the goal attainment method as Eq.(25):

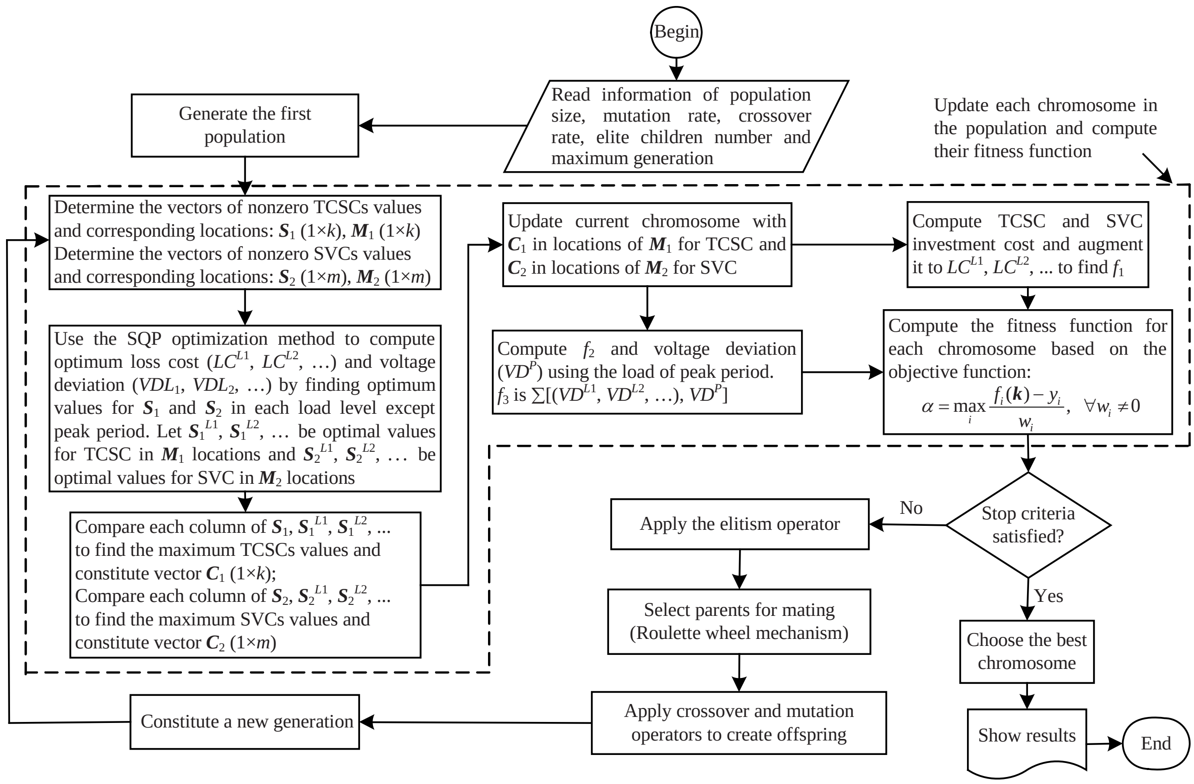

Fig.5 Combination of the genetic algorithm and goal attainment in the optimization process

$$\alpha = \max_i \frac{f_i(\boldsymbol{k}) - y_i}{w_i}, \quad \forall w_i \neq 0. \tag{25}$$

Note that a similar multi-objective optimization, which is a combination of SQP and the goal attainment method, is needed as a sub-problem during the computation of optimum loss cost and voltage deviation of each chromosome. Although SQP may get stuck in a local optimum, it is much faster than the GA. Due to this benefit and the fact that the SQP method is used just in sub-problems, the accuracy of the optimization procedure is not greatly affected.

EXAMPLE

The Iran Power Grid consists of 33780-km transmission lines (400 kV and 230 kV), which are geographically distributed through 16 major regional electric companies (RECs). Fars Regional Electric Company (FREC) is one of these companies with an approximate peak power demand of 2800 MW recorded in Summer 2007. FREC possesses 890- and 2618-km transmission lines of 400 kV and 230 kV, respectively. The FREC transmission network has been used to illustrate the performance and effectiveness of the proposed hybrid method. The information of lines, transformers, generators, network forecasted annual load profile, and initial compensators predicted for Summer 2010 are available in (Akbari *et al*., 2005). There are 52 buses of 230 kV and 400 kV, 75 transmission lines, 9 generators and 7 transformers based on the existing and accepted plan to supply customers in the target year. Seven tie lines connect FREC to its neighbours. The impact of neighbour networks is considered in this study for more accurate analysis. Therefore, the nearest power plants and all overhead lines that transmit the power to tie lines have been involved in this study. According to these effects, 14 buses, 22 transmission lines, 9 generators, and 1 transformer from neighbouring RECs have been added to the FREC network. Table 1 lists the necessary information for the economic study. In this table, the forecasted load curve, modeled by three load levels and their durations, has been considered to calculate power loss and voltage violation in the year of study for the allocation problem. In this investigation all lines and all load buses in the FREC network have been nominated for TCSC and SVC installation, respectively. TCSC compensation degree constraints have been assumed to be 70% of line reactance for TCSC in capacitive mode and 0% in inductive mode. Also, by considering 1 p.u. voltage of the bus where SVC is located, the susceptance can be changed between 1 p.u. and −1 p.u. in the power base of 100 MV·A.

Table 1 Information for economic study

Parameter	Value
Factor	
Level 1	0.81
Level 2	1.00
Level 3	0.90
Duration (h)	
Level 1	2136
Level 2	2832
Level 3	4392
Interest rate (%)	15
Active power cost ($/(kW·h))	0.16
Cost of power plant installation ($/kW)	1500
Life time of FACTS devices and power plants (year)	30

The vectors $\boldsymbol{y}$ and $\boldsymbol{w}$ have been initialized as $\boldsymbol{y}$=[0.95, 0.8, 0] and $\boldsymbol{w}$=[0.3, 0.3, 0.4]. Allocation results have been listed in Tables 2, 3 and 4. Based on allocated devices in Table 2, minimum loss and voltage deviation of each load level have been presented in Table 3, where generated power and cost (which are related to minimum loss and voltage deviation) have also been presented. Comparing data before and after allocation shows that optimum allocation causes loss reduction, generated power reduction, voltage profile enhancement and cost reduction for all load levels.

From Table 4 it is clear that after optimum allocation and installation of FACTS devices, the total cost of installation will be refunded by reducing the cost of the system performance (6.12% loss reduction and 2.69% peak power reduction) and in addition to this, a 2.4% savings will be achieved. It can be seen from Table 4 that the security margin and voltage profile have been improved with cost reduction of the FREC network simultaneously. Fig.6 shows the fitness function evaluation during the optimization procedure described in Fig.5. The voltage profile has been enhanced during the peak period after using FACTS devices as shown in Fig.7. Security margin

Table 2 The amount and location of TCSC and SVC

TCSC location		SVC location	Line compensation by TCSC (%)	SVC susceptance* (p.u.)
Initial bus	Final bus			
ASALUYEH400	ASALUYEH _P	ASALUYEH400	53.87	−0.215
DARAB230	FASA230	SOORMAGH400	20.55	0.496
DEHNO230	SHIRAZ230	ATOMI230	19.56	−0.484
FIROUZABAD230	FARS_P	DANESHGAH230	3.08	0.084
GENAVE230	GENAVE_P	DARAB230	41.05	0.981
LAR230	JAHROM1 230	FASA230	27.21	0.500
JAHROM_P	JAHROM1 230	LAR230	17.91	0.461
LAR230	JAHROM_P	MARVDASHT230	10.81	0.920
JAHROM_P	JAHROM2 230	SHIRAZ1 230	6.18	−0.027
SADI230	FARS_P	SHIRAZ2 230	1.25	0.750
SHIRAZ230	FARS_P	SOORMAGH230	24.66	0.687
SHIRAZ230	GHAEMIYE230	TIAFF-SIMAN	9.84	0.125

* Negative values mean inductive and positive values mean capacitive

Table 3 Optimum results based on allocated devices in each load level

Parameter	Before allocation			After allocation			Reduction (%)		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
Loss (×100 MV·A)	0.833	1.320	1.050	0.792	1.230	0.985	4.92	6.82	6.19
Generated power (×100 MV·A)	102.2	126.5	113.7	100.4	123.1	109.6	1.76	2.69	3.61
Voltage deviation	0.0040	0.0100	0.0100	0.0015	0	0.0060	62.50	100.00	40.00
Cost based on loss and generated power ($\times10^9$ $)	2.363	2.937	2.671	2.335	2.871	2.587	1.18	2.25	3.14

L1~L3 refer to load levels 1~3

Table 4 Optimum multi-objective results for the FREC network

Parameter	Before allocation	Objective value	After allocation	Reduction (%)
Loss (×100 MV·A)	3.203		3.007	6.12
Peak generation (×100 MV·A)	126.5		123.1	2.69
Total cost f_1 (3.0385×10^9 $)	1.000	0.950	0.976	2.40
f_2 (=1−SM)	0.902	0.800	0.854	5.32
f_3 (=$\sum VD_i$)	0.024	0	0.008	66.70
α	0.340		0.180	47.10

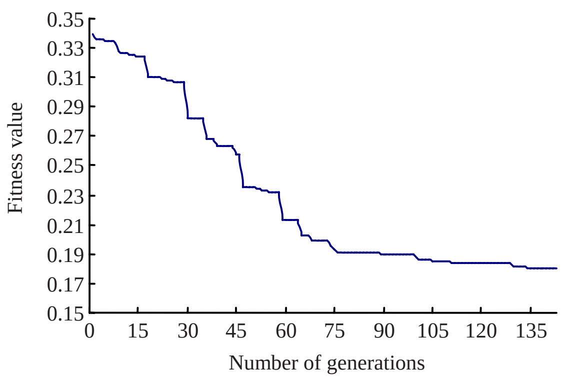

Fig.6 Fitness function evaluation during GA optimization

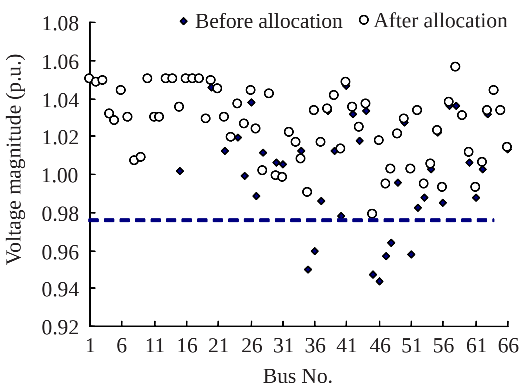

Fig.7 Voltage magnitude of FREC buses in peak load

improvement due to 5.32% reduction in f_2 implies that the FREC network becomes more robust against voltage collapse after the installation of FACTS devices. The eight most severe single-line outages are shown in Fig.8. It is obvious that after each outage, *SM* is greater than the initial values without the installation of FACTS devices.

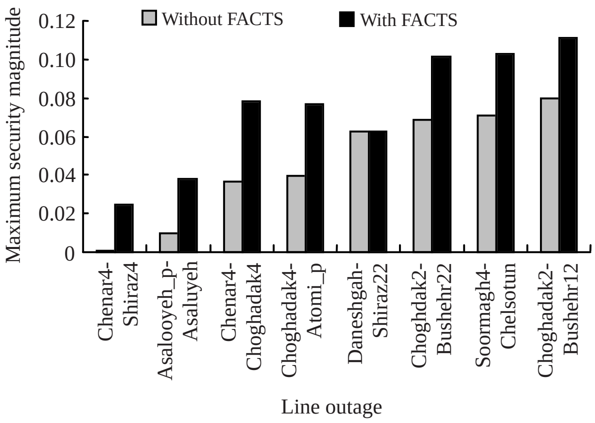

Fig.8 The eight most severe single-line outages and their related security margin with and without FACTS

Although GAs are considered to be time consuming methods, due to the off-line characteristic of planning problems this deficiency has no negative effect on the optimization procedure. Finding the optimum solution to simultaneously reduce all the objectives in a FACTS devices allocation problem is really vital for the prospective system, and therefore, it is worth spending more time on such an important decision. A comparative study between the proposed method and previous studies in (Chang and Huang, 1998; Gerbex *et al.*, 2001; Lu and Abur, 2002; Yorino *et al.*, 2003) reveals that, in order to carry out a comprehensive study of FACTS devices allocation, it is feasible to satisfy all the objectives simultaneously.

On the other hand, unlimited FACTS devices to reach the maximum loadability of a network (Gerbex *et al.*, 2001) cannot be practical, and it is possible to use a limited number of devices according to economic considerations.

CONCLUSION

In this paper a novel approach has been proposed to determine the optimum amounts and locations 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. In contrast to some previous researches, the cost objective function is considered along with other objectives to reach a precise and practical solution. In addition, the goal attainment method has been utilized to find the best compromise between conflicting objectives, even if the problem is nonconvex. According to the obtained results on the FREC network, a combination of the genetic algorithm and the goal attainment method results in the satisfaction of such allocation objectives as power loss reduction, investment cost reduction, security margin improvement, and voltage violation alleviation. It is also concluded that the entire investment of the FACTS devices is paid off and an additional 2.4% savings is made. Besides, the cost reduction of peak point power generation in this study implies that power plant expansion, providing the demand load, can be postponed.

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