ISSN 1996-3343

Asian Journal of Applied Sciences

Knowledgia
SCIENTIFIC
A Place to Publish Outstanding Research

http://knowledgiascientific.com

Asian Journal of Applied Sciences 5 (1): 1-19, 2012
ISSN 1996-3343 / DOI: 10.3923/ajaps.2012.1.19
© 2012 Knowledgia Review, Malaysia

A Novel Method for Optimal Placement of FACTS Based on Sensitivity Analysis for Enhancing Power System Static Security

[1]A. Samimi and [2]M.A. Golkar
[1]Department of Electrical Engineering, Islamic Azad University, Boroujerd Branch, Iran
[2]Department of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

Corresponding Author: A. Samimi, Department of Electrical Engineering, Islamic Azad University, Boroujerd Branch, Iran

ABSTRACT

In this study, a new method has been proposed to determine optimal location and best setting of FACTS controllers. Thyristor Controlled Series Compensator (TCSC) and static synchronous compensator (STATCOM) have been used for improving power system security. TCSC and STATCOM are employed for alleviation of congestion and enhancing voltage stability, respectively. Seeking the best place is performed using the sensitivity analysis. Then optimum rating of TCSC and best sizing of STATCOM is optimized using the genetic algorithm. The effect of TCSC on the network can be modeled as a controllable reactance inserted in the related transmission line. The average model can account for the high-frequency effects and power electronic losses and more accurately predict the active and reactive power outputs of the STATCOM. This paper employs the DIgSILENT simulator and the DPL as a programming tool of the DIgSILENT to show the validity of the proposed method. The effectiveness of suggested approach has been tested on IEEE 14-bus system.

Key words: TCSC, STATCOM, optimal placement, sensitivity analysis, genetic algorithm

INTRODUCTION

In recent years, with increasing development of power networks, the economical operation of power system is more considerable. Because of deregulation and restructuring of the electricity markets use of Flexible AC Transmission Systems (FACTS) devices is inevitable. The maximum capability of power systems can be exploited by means of FACTS devices. Nowadays, development of power electronics switches causes reduction in the cost of FACTS and therefore application of FACTS devices especially in distribution networks is more economical.

Because of the economical considerations, installation of FACTS controller in all the buses or the lines is impossible and unnecessary. There are several methods for finding optimal locations of FACTS devices in power systems.

According to Singh *et al.* (2007), a sensitivity based method has been suggested to optimally locate the Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controller (UPFC) for enhancing the system security under different operating conditions and at optimal settings of FACTS parameters. The DC power flow equations have been employed for calculating the sensitivity indices. Leung and Chung (1999) is used a Genetic Algorithm (GA) based method to determine the optimal sitting of FACTS controller in power system. The fitness function is to minimize the generation cost. Gerbex *et al.* (2001) used the genetic algorithm to seek the optimal location of multi-type FACTS devices in a power system. The optimizations are performed on three parameters: the location of the devices, their types and their values. According to Mori and Goto (2000), the Tabu Search (TS) method is used to solve the combinatorial (i.e., to determine number and location) problem of FACTS device allocation. Reference Gerbex *et al.* (2003) compare three heuristic methods, Simulated Annealing (SA), TS and GA, applied to the optimal location of FACTS devices in order to enhance the system security. The objective function is based on indices quantifying the severity of the contingencies in terms of branch loading and voltage levels. The three methods lead to similar results but generally TS and GA converge faster than SA to an optimal solution. In Singh *et al.* (2007), a real power flow performance sensitivity index has been proposed to decide optimal location of FACTS controllers. In study of Sharma *et al.* (2003), Extended Voltage Phasors Approach (EVPA) is proposed for placement of FACTS controllers in power systems within the voltage stability viewpoint.

In this study, a new method has been proposed to optimally locate TCSC and STATCOM in power systems. The suggested approach is composed of sensitivity analysis and the genetic algorithm. The search space in optimal placement of FACTS controllers in real power systems is usually sizable. Use of the approaches like sensitivity analysis can reduce the search space. Finding the best place for FACTS controllers is performed using the sensitivity analysis. Then the best setting of TCSC and sizing of STATCOM is managed using the genetic algorithm. The IEEE 14-bus system has been applied to test the suggested algorithm. DIgSILENT software which contains a powerful programming language called DPL has been prepared required facilities to execute the proposed algorithms and corresponding simulations.

TCSC MODELING

The IEEE defines the TCSC as a capacitive reactance compensator which consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR1 and SCR2. Series capacitive compensation has been used to increase line power transfer as well as to enhance system stability. The main circuit of a TCSC is shown in Fig. 1.

The firing angles of the thyristors are controlled to adjust the TCSC reactance according to the system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modeled as a fast switch between corresponding reactance offered to the power system. Assuming that the total current passing through the TCSC is sinusoidal, the equivalent reactance at the fundamental frequency can be represented as a variable reactance X_{TCSC}. The TCSC can be controlled to work either in the capacitive or the inductive zones avoiding steady state resonance. There exists a steady-state relationship between the firing angle α and the reactance X_{TCSC}. This relationship can be described by the following equation (Schaffner and Andersson, 2005):

$$X_{TCSC}(\alpha) = \frac{X_C X_l(\alpha)}{X_l(\alpha) - X_C} \tag{1}$$

where,

$$X_l(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \mathrm{Sin}\alpha} \tag{2}$$

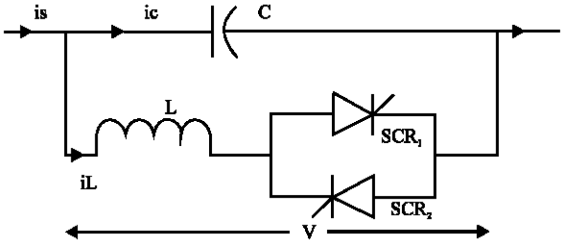

Fig. 1: Configuration of a TCSC

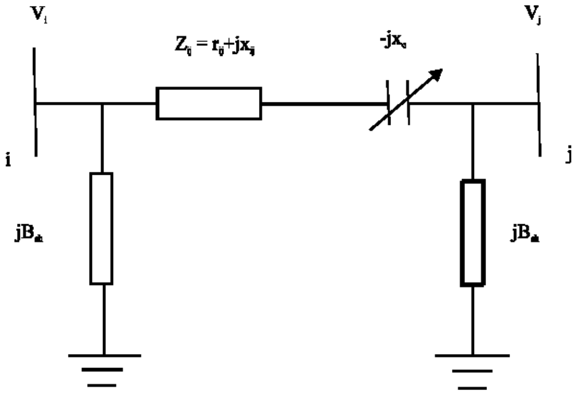

Fig. 2: Static model of line with TCSC

α is the firing angle, X_L is the reactance of the inductor and X_l is the effective reactance of the inductor at firing angle. In this study, the TCSC is taken as continuous varying capacitor. The effective series transmission impedance is given by:

$$X_{eff} = (1-k).X \tag{3}$$

where, k is the degree of series compensation as:

$$k = \frac{X_{TCSC}}{X} \qquad 0 \le k \le 1 \tag{4}$$

In the simulations of this study, only the capacitive region has been used. Hence, the compensation level varies from zero to the maximum level of 0.7. Figure 2 shows a transmission line with a TCSC.

In some references, a static Power Injection Model (PIM) of the TCSC has been presented. The injection model represents the TCSC as a device that injects certain amount of active and reactive power in a node (Singh *et al*., 2007).

$$P_{ic} = V_i^2 G'_{ij} - V_i V_j [G'_{ij} \cos(\delta_{ij}) + B'_{ij} \sin(\delta_{ij})] \tag{5}$$

$$Q_{ic} = -V_i^2 (B'_{ij} + B_{sh}) - V_i V_j [G'_{ij} \sin(\delta_{ij}) - B'_{ij} \cos(\delta_{ij})] \tag{6}$$

$$P_{jc} = V_j^2 G'_{ij} - V_i V_j [G'_{ij} \cos(\delta_{ij}) - B'_{ij} \sin(\delta_{ij})] \tag{7}$$

$$Q_{jc} = -V_j^2 (B'_{ij} + B_{sh}) + V_i V_j [G'_{ij} \sin(\delta_{ij}) + B'_{ij} \cos(\delta_{ij})] \tag{8}$$

where:

$$G'_{ij} = \frac{r_{ij}}{r^2_{ij} + (x_{ij} - x_c)^2} \tag{9}$$

$$B'_{ij} = \frac{-(x_{ij} - x_c)}{r^2_{ij} + (x_{ij} - x_c)^2} \tag{10}$$

STATCOM MODELING

It is also essential to model STATCOM to be adapted for the power flow program. In previous studies on placement of STATCOM, The STATCOM is traditionally modeled for power flow analysis as a PV or PQ bus depending on its primary application. The active power is either set to zero (neglecting the STATCOM losses) or calculated iteratively. Using average theory, STATCOM can be modeled in power flow analysis carefully and calculation of accurate losses of STATCOM has been provided. Averaging technique is a common approach to the modeling of power converters. Switch-mode converters have a discontinuous behavior which is analytically very complex. There exists a set of State Space Equations (SSE) that mathematically models the exact system. Thus, the number of switching periods during the synchronous period establishes the number of SSE to be analyzed. Averaging technique approximates the modulation of the converter DC/AC from a periodic discontinuous waveform to a periodic continuous one.

Let the angle α be defined as the phase separation between the fundamental components of output voltage of STATCOM and power system voltage at coupling bus. To provide the required active and reactive powers by STATCOM, α varies in a small nonzero region around zero ($\alpha \epsilon [-1.5°, 1.5°]$). Equivalent circuit average model of STATCOM is shown in Fig. 3, including time-dependent sources (Bina and Hamill, 2005).

The total power losses of STATCOM is function of the phase shift between the converter output and the power system voltage (α) and can be obtained by the average model in steady state. The circuit in Fig. 3 was analyzed at various angles α to obtain the losses of STATCOM. The simulation of this circuit was programmed by MATLAB. Figure 4 shows STATCOM power losses (P) as a percentage of STATCOM rating (Q) against the phase shift (α) that is obtained by the average model.

In Fig. 3, functions f_1 and f_2 represent two linear combination of the three-phase power system phase-neutral voltages ($v_a(t)$, $v_b(t)$ and $v_c(t)$) as follows:

$$\begin{aligned} f_1(V(t)) &= 2v_a(t) - v_b(t) - v_c(t) \\ f_2(V(t)) &= 2v_b(t) - v_a(t) - v_c(t) \end{aligned} \tag{11}$$

Also, two dependent voltage sources g_1 and g_2 are defined by:

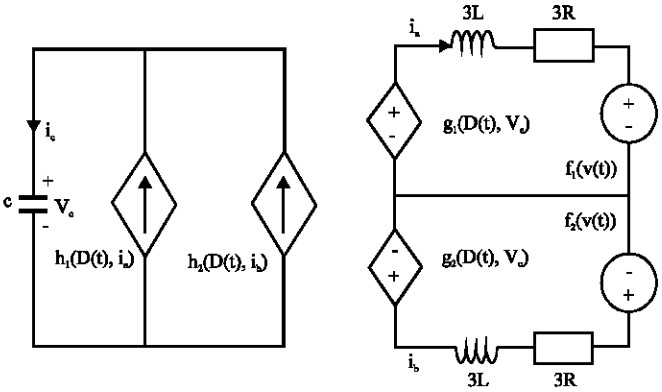

Fig. 3: Equivalent circuit average model of STATCOM

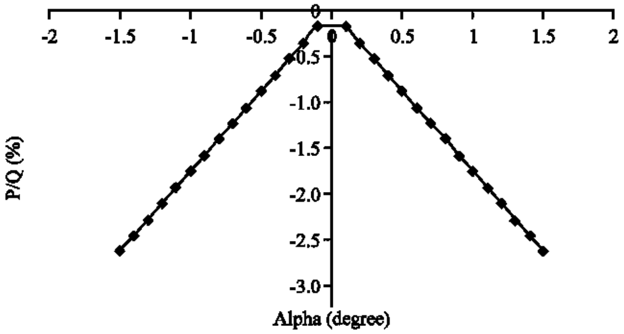

Fig. 4: Percent of losses (P/Q) of STATCOM

$$\begin{aligned} g_1(D(t), V_C) &= (2D_a(t) - D_b(t) - D_c(t))V_C \\ g_2(D(t), V_C) &= (2D_b(t) - D_a(t) - D_c(t))V_C \end{aligned} \tag{12}$$

And two dependent current sources h_1 and h_2 as:

$$\begin{aligned} h_1(D(t), i_a(t)) &= (D_c(t) - D_a(t))i_a(t) \\ h_2(D(t), i_b(t)) &= (D_c(t) - D_b(t))i_b(t) \end{aligned} \tag{13}$$

where, $D_a(t)$, $D_b(t)$ and $D_c(t)$ are the three-phase duty ratio functions (Bina and Hamill, 2005).

Whereas, the average model presents a time-dependent circuit, a phasor PQ or PV model is essential for the power flow analysis. Hence, here it is performed adaptive analysis to get the supplied active and reactive powers of STATCOM (P_{CON} and Q_{CON}). A new bus is added for every STATCOM as the converter AC voltage which is connected to an existing bus n through the commutation reactance (X_{CON}) and the AC resistance (R). Ignoring R for big X_{CON}/R ratios, the active and reactive power of the compensator can be obtained by the well-known power relationships for two buses that are connected through a connecting reactance:

$$P_{CON} = \frac{V_t V_{CON}}{X_{CON}} \sin(\alpha - \frac{\pi}{M}) \; Q_{CON} = \frac{V_{CON}}{X_{CON}}(V_{CON} - V_t \cos(\alpha - \frac{\pi}{M})) \tag{14}$$

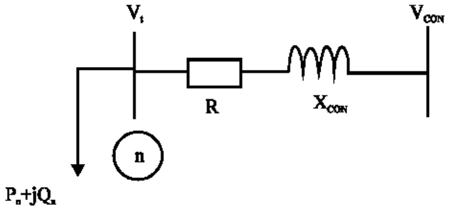

Fig. 5: The adapted average model of STATCOM for power flow analysis

Where V_t and V_{CON} are the magnitude of the fundamental voltages of bus n and the converter AC bus, respectively. Figure 5 describes the power flow model, including the above parameters. P_n and Q_n are active and reactive powers of the power system at bus-n (Bina *et al.*, 2005).

SENSITIVITY ANALYSIS FOR OPTIMAL PLACEMENT OF TCSC

Many sensitivity performance indices have been proposed for the analysis of power systems. There are some sensitivity indices which have the most attraction for optimal placement of series compensators.

Reduction of total system reactive power loss index: Here, we look at a method based on the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC. For TCSC placed between buses i and j, we consider net line series reactance as a control parameter. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as (Taher and Besharat, 2008):

$$a_{ij}=\frac{\partial Q_L}{\partial x_{ij}}=[V_i^2+V_j^2-2V_iV_j\cos\delta_{ij}].\frac{r_{ij}^2-x_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} \tag{15}$$

In this method TCSC must be installed in a line having the most positive loss sensitivity index.

Line loss sensitivity index: The sensitivity a_k of transmission loss (P_{Lk}) on a series compensated line-k connected between bus-i and bus-j with respect to series capacitive reactance (X_{ck}) is defined as follows (Singh and David, 2000):

$$a_k=\left.\frac{\partial P_{Lk}}{\partial X_{ck}}\right|_{X_{ck}=0}=-2[V_i^2+V_j^2-2V_iV_j\mathrm{Cos}\delta_{ij}]G_{ij}B_{ij} \tag{16}$$

Total system loss sensitivity index: The real power loss of a system having N bus is:

$$P'_{LT}=\sum_{j=1}^{N}\sum_{k=1}^{N}[\alpha_{jk}(P_jP_k+Q_jQ_k)+\beta_{jk}(Q_jP_k-P_jQ_k)] \tag{17}$$

where, P_j and Q_j, respectively, are the real and reactive power injected at bus-j and α, β are the loss coefficients defined by:

$$\alpha_{jk} = \frac{r_{jk}}{V_j V_k} \mathrm{Cos}(\delta_j - \delta_k) \tag{18}$$

$$\beta_{jk} = \frac{r_{jk}}{V_j V_k} \mathrm{Sin}(\delta_j - \delta_k) \tag{19}$$

where, r_{jk} is the real part of the j-kth element of Z_{bus} matrix. Using power injection model of FACTS this total loss if FACTS device, one at a time is used, can be written as:

$$P_{LT} = P'_{LT} - (P_{ic} + P_{jc}) \tag{20}$$

The total system real power loss sensitivity factors with respect to the parameters of TCSC placed at line-k can be defined as:

$$b_k = \left.\frac{\partial P_{LT}}{\partial X_{ck}}\right|_{X_{ck}=0} \tag{21}$$

Consider a line-k connected between bus-i and bus-j. The total system loss sensitivity with respect to TCSC can be derived as given below:

$$\begin{aligned} b_k = {} & \left.\frac{\partial P_{LT}}{\partial P_i}\frac{\partial P_i}{\partial X_{ck}}\right|_{X_{ck}=0} + \left.\frac{\partial P_{LT}}{\partial P_j}\frac{\partial P_j}{\partial X_{ck}}\right|_{X_{ck}=0} + \left.\frac{\partial P_{LT}}{\partial Q_i}\frac{\partial Q_i}{\partial X_{ck}}\right|_{X_{ck}=0} \\ & + \left.\frac{\partial P_{LT}}{\partial Q_j}\frac{\partial Q_j}{\partial X_{ck}}\right|_{X_{ck}=0} - \left.\left(\frac{\partial P_{ic}}{\partial X_{ck}} + \frac{\partial P_{jc}}{\partial X_{ck}}\right)\right|_{X_{ck}=0} \end{aligned} \tag{22}$$

where:

$$\frac{\partial P_{LT}}{\partial P_i} = 2\sum_{m=1}^{N} [\alpha_{im} P_m - \beta_{im} Q_m] \tag{23}$$

$$\frac{\partial P_{LT}}{\partial Q_i} = 2\sum_{m=1}^{N} [\alpha_{im} Q_m + \beta_{im} P_m] \tag{24}$$

$$\left.\frac{\partial P_i}{\partial X_{ck}}\right|_{X_{ck}=0} = \left.\frac{\partial P_{ic}}{\partial X_{ck}}\right|_{X_{ck}=0} = -2[V_i^2 - V_i V_j \cos\delta_{ij}].\frac{r_{ij}\,x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} - V_i V_j \sin\delta_{ij} \frac{r_{ij}^2 - x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \tag{25}$$

$$\left.\frac{\partial P_j}{\partial X_{ck}}\right|_{X_{ck}=0} = \left.\frac{\partial P_{jc}}{\partial X_{ck}}\right|_{X_{ck}=0} = -2[V_j^2 - V_i V_j \cos\delta_{ij}].\frac{r_{ij}\,x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} + V_i V_j \sin\delta_{ij} \frac{x_{ij}^2 - r_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \tag{26}$$

Introducing a new real power flow sensitivity index: Here, a new real power flow sensitivity index with respect to the parameter of TCSC placed in line-j is introduced as:

$$FSI_j = \sum_{m=1}^{N_l} \beta_m \frac{\partial P_m}{\partial X_j} \tag{27}$$

In this index, TCSC has been modeled as a variable series capacitive reactance X_{TCSC}. Therefore, the total line reactance decreases. This index demonstrates the sum of variation of real power flow in all lines with respect to the change of reactance of line-j. β_m is a weighted factor which can be selected higher for congested lines. For this study β_m is selected five for congested lines.

Calculating of the FSI_j index can be performed using DC power flow equations. But for accurate calculation, this index is computed using AC power flow. For this purpose, the line reactance would be very little changed around the operating point subject to the other conditions are fixed. Hence, FSI_j can be rewritten as:

$$FSI_j = \sum_{m=1}^{N_l} \beta_m \left.\frac{\Delta P_m}{\Delta X_j}\right|_{\Delta X_j \to 0} \tag{28}$$

This index is calculated for all the lines. After that FSI_{min} and FSI_{max} are specified by sorting the FSI values, normalized real power flow index is defined as:

$$FSIn_j = \frac{FSI_j - FSI_{min}}{FSI_{max} - FSI_{min}} \tag{29}$$

TCSC must be placed in a line having the most positive sensitivity index.

SENSITIVITY ANALYSIS FOR OPTIMAL PLACEMENT OF STATCOM

Voltage sensitivity index: Voltage Sensitivity Index (VSI) at bus-j is defined as:

$$VSI_j = \sum_{i=1}^{N} \alpha_i \frac{\partial V_i}{\partial Q_j}\ j = 1, 2 \text{ and } N_{Load} \tag{30}$$

Where:

V_i : Voltage magnitude at bus i

Q_j : Reactive power injection at bus i

This index demonstrates the sum of variation of voltage magnitude in all the buses with respect to the change of reactive power of bus j. α_i is a weighted factor which can be selected higher for buses having voltage drop.

Loss sensitivity index: Loss sensitivity index can be used for initial choosing the buses of power system which require compensation of the reactive power. Consider a system having N buses, first Ng being the generator buses and Ng+1,... , N as the load buses. The Loss Sensitivity Index (LSI) with respected to reactive power output of a source placed at a bus-i, has been defined as (Tyagi and Srivastava, 2006):

$$a_i = \frac{\partial P_{Loss}}{\partial Q_i} \qquad i = N_{g+1},\ldots,N \tag{31}$$

where, Q_i is the reactive power injected at the load bus i, P_{Loss} is the real power transmission loss of the system. A reactive power source should be placed at a load bus-i, having most negative sensitivity index a_i.

Introducing a new combination sensitivity index: The use of only loss sensitivity index to find optimal placement of compensators may cause to select the places having low reactive load. Hence, these places are not seemed suitable location for compensation economically. However, VSI proposes suitable places apparently but because reducing of the system losses which is one of the main goals of optimization is not considered, this index is not a complete criterion to choose the optimum locations.

To solve the defect has been mentioned, in this section a new index including all the optimization goals has been introduced. Considering that improvement of voltage stability and reduction of system losses are the main goals of optimization for optimal placement of STATCOM, proposed index called compound voltage-loss sensitivity index has been defined as:

$$VLSI(j) = a \times VSI_n(j) + b \times LSI_n(j) \quad j = 1, 2, \ldots, N \tag{32}$$

where, subscript n demonstrates normalized values. N is the number of buses, VSI is voltage sensitivity index, LSI is loss sensitivity index, a, b is weighted factors.

The index calculation is in the way that firstly, voltage sensitivity analysis is executed and VSI is defined for all buses. Then VSI_{min} and VSI_{max} are specified by sorting the VSI values, normalized voltage sensitivity index is defined as:

$$VSI_n(j) = \frac{VSI(j) - VSI_{min}}{VSI_{max} - VSI_{min}} \tag{33}$$

In the next stage, loss sensitivity analysis is executed for all buses and normalized loss sensitivity index is calculated as:

$$LSI(j) = -\frac{\partial P_{Loss}}{\partial Q_j} \tag{34}$$

$$LSI_n(j) = \frac{LSI(j) - LSI_{min}}{LSI_{max} - LSI_{min}} \tag{35}$$

The weighted factors a, b present the significance of each one of the goals, improvement of voltage stability and reduction of system losses in the optimization problem. It is clear that other important optimization goal, i.e., decrease in reactive power of network has been concealed.

OPTIMAL SETTING OF FACTS CONTROLLERS USING THE GENETIC ALGORITHM

The genetic algorithm has been used to find the optimum setting of TCSC and sizing of STATCOM. Genetic algorithms are based on the mechanisms of natural selection. The principles and details of the genetic algorithm have been presented in many references.

Objective function for optimal setting of TCSC: The objective function (F) has been made of the severity of the system loading by the following relationship:

$$F = \frac{1}{SL} \tag{36}$$

$$SL = \sum_{m=1}^{N_1} \left(\frac{S_{Lm}}{S_{Lm}^{max}}\right)^{2n} \tag{37}$$

Where:

SL = System loading factor

S_{LM} = Apparent power flow in line m

S_{Lm}^{max} = The rated capacity of line-m

N_1 = The number of power system lines

The system loading factor SL will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for given state of the power system. Most of the works on contingency selection algorithms utilize the second order performance indices which, in general, suffer from masking effects. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order performance indices. However, in this study, the value of exponent has been taken as 2.

Objective function for optimal sizing of STATCOM: The objective function (F) has been made from the two terms by the following relationships:
Maximize:

$$F = \frac{VS}{SL} \tag{38}$$

Where:

VS: Voltage stability index

This objective function is including improvement of voltage stability (VS) and alleviation of loading of congested lines in power system (SL). The VS index demonstrates the condition of network from the viewpoint of voltage stability. This index is calculated with the relation:

$$VS = \sum_{i=1}^{N} V_F(i) \tag{39}$$

Where:
N: The total number of buses in the power system

$$V_F(i) = \begin{cases} e^{(-100\times|u_i-0.95|)} & u_i < 0.95 \\ 1 & 0.95 \le u_i \le 1.05 \\ e^{(-100\times|u_i-1.05|)} & u_i > 1.05 \end{cases} \tag{40}$$

Where:
u_i: Voltage at bus i_{th} in per unit

When the voltage magnitude of every power system bus lies within [0.95, 1.05] p.u., then $V_F(i) = 1$, otherwise the value $V_F(i)$ decreases exponentially with the voltage deviation. Figure 6 shows the curve of $V_F(i)$.

The stability of network from the viewpoint of voltage is better for the more amount of VS. It is important to notice that only the steady state stability in this study was considered.

Initial population: Some responses as chromosomes of initial population must be created for starting algorithm.

Selection operator: The best solutions in the current population are selected by roulette wheel technique.

Crossover operator: Two random chromosomes in the middle generation are selected. Then a random number (n) between 1 to the length of chromosome are selected and pairs of selected chromosomes from n-th gene to later are swapped to each other to produce new chromosomes.

Mutation operator: To test each element for fitness and to avoid algorithm stopping at a local optimum some solutions are also randomly modified. Therefore a chromosome is selected randomly, then some of it genes are replaced with another random numbers.

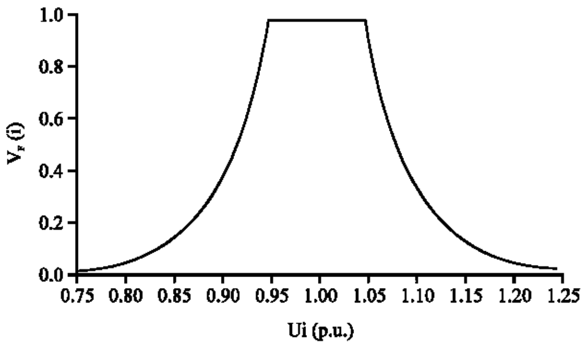

Fig. 6: Function V_F

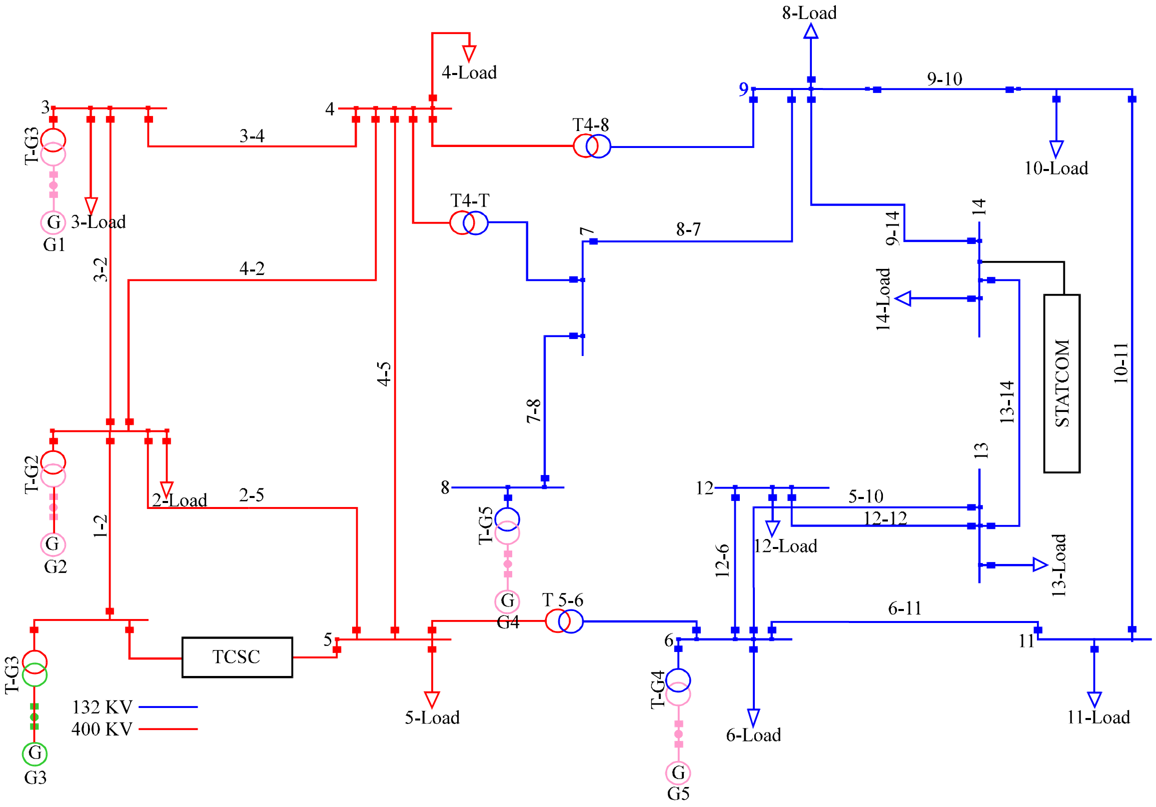

Fig. 7: The IEEE 14-bus system in DigSILENT

NUMERICAL RESULTS AND DISCUSSION

The case study for examination of the proposed algorithm is the IEEE 14-bus system. The single line diagram of this system depicted in DIgSILENT software is shown in Fig. 7.

All the loads of IEEE 14-bus system have been modeled by the following polynomial equations:

$$P = P_0 \left(\frac{V}{V_0} \right)^{\alpha} \tag{41}$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^{\beta} \tag{42}$$

where, P_0 and Q_0 stand for the real and reactive powers consumed at a reference voltage V_0. In this study, the value of exponents have been taken as $\alpha = 1.6$ and $\beta = 1.8$. In addition, a 30% increasing coefficient for active and reactive power loads rather than the base values is considered.

Optimal placement of TCSC: Having been calculated the real power flow sensitivity indices, the results are shown in Table 1. Regarding to the results shown in Table 1, line 1-5 has the most positive sensitivity index. Therefore, this line is selected for installing of TCSC. Figure 7 shows the location of TCSC in IEEE 14-bus system. Analyzing the results of loading, it was clear this place is close to the congested line 1-2. Figure 3 shows the situation of this place on the network. The degree of compensation (k) is calculated as 59% by implementing the genetic algorithm.

Table 1: The real power flow sensitivity indices

Line	FSI(j)	FSI_n(j)
1-2	-24.2878	0
1-5	12.4146	1
10-11	-0.0126	0.6614
12-13	-0.0218	0.6612
12-6	-0.1296	0.6582
14-13	-0.0110	0.6614
2-5	-5.0649	0.5238
3-2	1.3038	0.6973
3-4	-0.3280	0.6528
4-2	-2.6979	0.5882
4-5	2.3310	0.7253
6-11	0.0074	0.6620
6-13	0.3161	0.6704
7-8	0.0132	0.6621
9-10	-0.0588	0.6601
9-14	0.0117	0.6621
9-7	-0.3549	0.6521

Table 2: Loading of lines before and after placing TCSC

Line	Rated voltage (kV)	Rating (MVA)	Loading without TCSC (%)	Loading with TCSC (%)
1-2	132	150	138.5	106.2
1-5	132	150	65.5	97.4
10-11	400	50	15.7	19.1
12-13	400	50	4.0	4.4
12-6	400	50	22.2	22.4
14-13	400	50	15.7	18.0
2-5	132	150	35.3	21.8
3-2	132	150	63.5	58.1
3-4	132	150	22.8	28.4
4-2	132	150	48.2	37.7
4-5	132	150	56.6	70.6
6-11	400	50	20.8	24.3
6-13	400	50	51.1	52.3
7-8	400	60	40.2	40.0
9-10	400	50	33.2	33.3
9-14	400	50	35.8	34.8
9-7	400	75	17.2	17.3

Table 2 shows the loading of lines in the base state and after placing TCSC in line 1-5. The most congested line has a 138.5% loading in the base state. After installing TCSC in line 1-5 the loading of line 1-2 decreases to 106.2% in exchange for a loading increment of line 1-5 and line 4-5. As previously mentioned, by most of the operational standards, the system with one huge violation is much more severe than that with many small violations. As it is seen in Table 2, the loading changes of other lines are negligible. The result of optimal placement of TCSC via suggested approach corresponds to the results of other approaches in other references Shi *et al.* (2007) and Acharya and Mithulanantan (2007). Therefore, the validity of the proposed method is confirmed.

Table 3: Voltage magnitude of buses before and after placing TCSC

Bus	Voltage in p.u. without TCSC	Voltage in p.u. with TCSC
1	1.060	1.060
2	1.021	1.027
3	0.971	0.976
4	0.971	0.976
5	0.986	0.990
6	0.918	0.922
7	0.952	0.957
8	0.995	0.999
9	0.939	0.943
10	0.924	0.928
11	0.916	0.920
12	0.898	0.902
13	0.894	0.898
14	0.892	0.896

Other results of load flow calculation before and after installing of TCSC are shown in Table 4

Table 4: Results of load flow calculation before and after compensation with TCSC

Parameter	Without TCSC	With TCSC
Active power generation (MW)	362.25	363.36
Reactive power generation (MVAr)	162.77	142.82
Active losses (MW)	25.55	26.66
Reactive losses (MVAr)	62.15	42.20
P_{loss} (%)	7.05%	7.34%
SL	4.335	2.697

Bus voltage level before and after compensation process is shown in Table 3. In spite of effective relief of congestion, it is clear the improvement of voltage stability is negligible and there is impermissible voltage drop at some of the buses.

Optimal placement of STATCOM: Analyzing the results of load flow, it can be seen that the voltage drop problem is more serious than loss of system. Therefore, factor b in VLSI relationship is assumed as zero. After the implement of sensitivity analysis on the network, the VSI indices are calculated for all buses. From the Table 5, it is found that the bus-14 has the most sensitivity index and is selected for installing of STATCOM. Figure 4 shows the situation of this place on the network. By analyzing the voltage profile, it was clear that this bus has the most voltage drop in the network. Therefore, it has been considered to install the compensator. The optimal place of STATCOM based on the suggested approach corresponds to the results of another approach (Bina *et al.*, 2005). Therefore the accuracy of the suggested method will be confirmed.

For the first study F = VS/FL has been considered as the objective function. Using the genetic algorithm the optimum sizing of STATCOM is calculated as 0.6 p.u. After installing STATCOM in bus-14, the load flow results show that the voltage magnitude of every power system bus is within their permissible limits. Table 6 shows the voltage magnitude of buses before and after placing STATCOM. The loading of lines are shown in Table 7. Although installing STATCOM in bus-14 can improve the voltage stability of power system, congestion has not been relieved.

Table 5: Voltage sensitivity index for buses

Bus	VSI	VSI_n
1	-0.000032	0.0
10	-0.016274	0.90459
11	-0.016276	0.90471
12	-0.01672	0.92943
13	-0.016523	0.91846
14	-0.017987	1.0
2	-0.007562	0.41938
3	-0.013361	0.74236
4	-0.014741	0.81921
5	-0.013612	0.75634
6	-0.013831	0.76853
7	-0.014827	0.82400
8	-0.01701	0.94559
9	-0.015079	0.83804

Table 6: The Voltage magnitude of buses before and after placing STATCOM

Bus	Voltage in p.u. without STATCOM	Voltage in p.u. with STATCOM
1	1.060	1.060
2	1.021	1.037
3	0.971	0.999
4	0.971	1.007
5	0.986	1.021
6	0.918	0.950
7	0.952	0.987
8	0.995	1.000
9	0.939	0.976
10	0.924	0.961
11	0.916	0.951
12	0.898	0.944
13	0.894	0.950
14	0.892	1.028

Furthermore from the Table 8, it is found that the power loss has not been decreased. Because P_{loss} is not considered in optimal placement of STATCOM issue. For the next study

$$F = \frac{VS}{SL \times P_{loss}}$$

has been considered as the objective function. The optimal location of STATCOM is determined based on VLSI index. Since, the voltage stability is more important in this network, the value of weighted factors are taken as a = 2 and b = 1. Table 9 shows the value of VLSI for the buses. Despite the bus-8 has the most value of VLSI, it is not suitable for installing STATCOM, because it has a synchronous compensator. Therefore, placing STATCOM in this bus is ineffective. Here, bus-9 is suggested for installing a STATCOM with nominal power of 1.14 p.u. Table 8 shows the load flow results after installing the STATCOM in bus-9. From the Table 10, a 0.72% reduction in power losses is obvious instead of a 90% increment in sizing of STATCOM.

Table 7: Loading of lines before and after placing STATCOM

Line	Loading without STATCOM (%)	Loading with STATCOM (%)
1-2	138.5	138.9
1-5	65.5	65.2
10-11	15.7	16.8
12-13	4.0	9.3
12-6	22.2	19.9
14-13	15.7	52.2
2-5	35.3	34.9
3-2	63.5	61.8
3-4	22.8	21.2
4-2	48.2	47.2
4-5	56.6	55.6
6-11	20.8	20.5
6-13	51.1	54.9
7-8	40.2	12.3
9-10	33.2	34.1
9-14	35.8	58.8
9-7	17.2	13.8

Table 8: Loading of lines after placing STATCOM based on various objective functions

Parameter	With STATCOM $F = \frac{VS}{SL}$	With STATCOM $F = \frac{VS}{SL \times P_{loss}}$
Active power generation (MW)	363.60	360.70
Reactive power generation (MVAr)	102.31	44.10
Active losses (MW)	26.89	24.09
Reactive losses (MVAr)	61.84	57.47
P_{loss}(%)	7.40	6.68

Table 9: VLSI for the buses

Bus	VSI_n	LSI_n	VLSI
1	0.0	0.0	0.0
10	0.90459	0.08388	1.89307
11	0.90471	0.16735	1.97676
12	0.92943	0.26366	2.12253
13	0.91846	0.36932	2.20624
14	1.0	0.48725	2.48725
2	0.41938	0.52438	1.36314
3	0.74236	0.57743	2.06215
4	0.81921	0.64952	2.28795
5	0.75634	0.71974	2.23241
6	0.76853	0.79085	2.32792
7	0.82400	0.86280	2.51081
8	0.94559	0.92886	2.82003
9	0.83804	1.0	2.67608

The voltage magnitude of buses after placing a STATCOM with nominal power of 1.14 p.u in the bus-9 based on various objective functions is shown in Table 10. As it is seen in the Table 10, the voltage stability has been improved in both of the instances. But the rating of STATCOM in the second case is 90% greater than the first one.

Table 10: The Voltage magnitude of buses after placing STATCOM based on various objective functions

Bus	Voltage in p.u. With STATCOM $F=\frac{VS}{SL}$	Voltage in p.u. with STATCOM $F=\frac{VS}{SL\times P_{loss}}$
1	1.060	1.060
2	1.038	1.044
3	0.999	1.010
4	1.008	1.040
5	1.021	1.041
6	0.951	0.968
7	0.987	1.019
8	1.000	1.008
9	0.977	1.014
10	0.962	0.996
11	0.952	0.977
12	0.945	0.952
13	0.951	0.950
14	1.030	0.961

Table 11: Loading of lines after placing STATCOM and TCSC

Line	Loading without FACTS (%)	Loading with STATCOM and TCSC (%)
1-2	138.5	108.7
1-5	65.5	99.0
10-11	15.7	20.7
12-13	4.0	11.5
12-6	22.2	20.8
14-13	15.7	63.3
2-5	35.3	21.0
3-2	63.5	57.0
3-4	22.8	26.3
4-2	48.2	37.0
4-5	56.6	69.2
6-11	20.8	24.4
6-13	51.1	61.2
7-8	40.2	11.9
9-10	33.2	35.6
9-14	35.8	70.3
9-7	17.2	13.3

Optimal placement of STATCOM and TCSC: Regarding the previous results, it is found that using of only TCSC or STATCOM cannot ensure all objectives of power system security. Considering the sensitivity indices obtained in the previous sections, the best location for installing TCSC and STATCOM are line 1-5 and the bus-14, respectively. The degree of compensation of TCSC is taken as 59% and the optimum rating of STATCOM is calculated as 0.734 p.u. Table 11 and 12 show line loading and voltage magnitude after optimization by FACTS controllers.

From the Table 11, it is found that the loading of congested line after optimization has been reduced as 108.7%. Therefore, there is a 2.5% increasing in loading rather than the first case (presence of only TCSC) due to dependency of loads to voltage. Because the STATCOM has improved the voltage magnitude of all buses and then the loads have increased slightly. The result

Table 12: The Voltage magnitude of buses after placing STATCOM and TCSC

Bus	Voltage in p.u. without FACTS	Voltage in p.u. with STATCOM and TCSC
1	1.060	1.060
2	1.021	1.040
3	0.971	1.000
4	0.971	1.007
5	0.986	1.017
6	0.918	0.948
7	0.952	0.987
8	0.995	1.000
9	0.939	0.977
10	0.924	0.961
11	0.916	0.950
12	0.898	0.944
13	0.894	0.952
14	0.892	1.028

of load flow calculation before and after compensation process with STATCOM and TCSC shows improvement of voltage stability and congestion relief. These results are found in Table 11 and 12. Therefore, the power system security will be ensured.

CONCLUSION

In this study, a new method has been proposed to optimally locate FACTS in power systems. The suggested approach is composed of sensitivity analysis and genetic algorithm. First, the appropriate modeling of the FACTS has been presented. Then, sensitivity analysis approach has been utilized to find optimal placement of series and shunt compensators. In this process, a real power flow sensitivity index and combination voltage-loss sensitivity index have been presented. Finally, the optimum setting of FACTS has been defined by GA. The objective function has been made of the severity of the system loading and voltage stability. The result of load flow calculation before and after compensation process shows the validity of proposed algorithms.

REFERENCES

Acharya, N. and N. Mithulananthan, 2007. Locating of series FACTS devices for congestion management in deregulated electricity markets. Electr. Power Syst. Res., 77: 352-360.

Bina, M.T. and D.C. Hamill, 2005. Average circuit model for angle-controlled. Statcom Electric Power Appl., 152: 653-659.

Bina, M.T., J.R. Siahbidi and K. Kanzi, 2005. Application of averaging technique to the power system optimum placement and sizing of static compensators. Proceedings the of the 7th International Power Engineering Conference, November 29-December 2, 2005, Singapore, pp: 1-6.

Gerbex, S., R. Cherkaoui and J.A. Germond, 2001. Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms. Power Syst. IEEE Transact., 16: 537-544.

Gerbex, S., R. Cherkaoui and A.J. Germond, 2003. Optimal location of FACTS devices to enhance power system security. Proceedings of the Power Tech Conference, June 23-26, 2003, IEEE Bologna.

Leung, H.C. and T.S. Chung, 1999. Optimal placement of FACTS controller in power system by a genetic based algorithm. Proc. IEEE Int. Conf. Power Electronics Drive Syst., 2: 833-836.

Mori, H. and Y. Goto, 2000. A parallel Tabu search based method for determining optimal allocation of FACTS in power systems. Proceedings of the International Conference on Power System Technology, December 4-7, 2000, Perth, WA., pp: 1077-1082.

Schaffner, C. and G. Andersson, 2005. Performance of a TCSC for congestion relief. Proceedings of the IEEE Russia International Conference on Power Tech, June 27-30, 2005, St. Petersburg, pp: 1-7.

Sharma, N.K., A. Ghosh and R.K. Varma, 2003. A novel placement strategy for facts controllers. IEEE Trans. Power Delivery, 18: 982-987.

Shi, Y., K. Mwanza and L.A. Tuan, 2007. Valuation of FACTS for managing congestion in combined pool and bilateral markets. Proceedings of the IEEE Power Engineering Society Conference and Exposition in Africa, July 16-20, 2007, Johannesburg, South Africa, pp: 1-7.

Singh, J.G., S.N. Singh and S.C. Srivastava, 2007. Enhancement of power system security through optimal placement of TCSC and UPFC. Proceedings of the Power Engineering Society General Meeting, June 24-28, 2007, Tampa, FL., pp: 1-6.

Singh, S.N. and A.K. David, 2000. Congestion management by Optimizing FACTS device location. Proceedings of the IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, April 4-7, 2000, London, UK., pp: 23-28.

Taher, S.A. and H. Besharat, 2008. Transmission congestion management by determining optimal location of FACTS devices in deregulated power systems. Am. J. Applied Sci., 5: 242-247.

Tyagi, B. and S.C. Srivastava, 2006. A method for optimal placement of reactive sources and reactive power procurement in competitive electricity markets. Proceedings of the Power India Conference, June 5, 2006, New Delhi, pp: 6.