which the loadability cannot be improved. Besides, these devices are located at buses that are weak from reactive power requirements.

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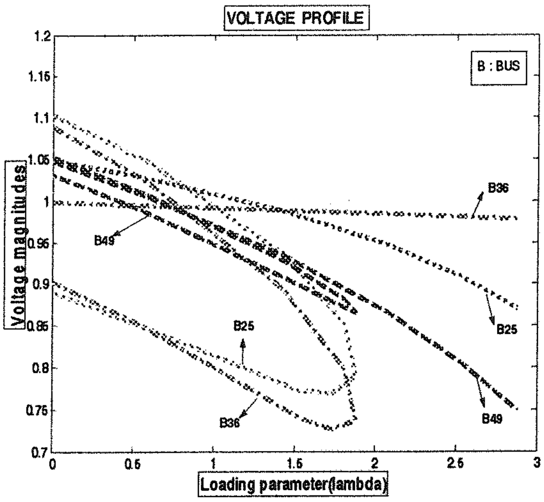

Figure 6: P-V comparison curve for two case
(with and without STATCOM allocation)

In Figure 8 all bus voltages profile are shown before and after STATCOM placement in test system. Results indicate that after STATCOM allocation we have a flatter voltage profile, moreover optimal placement of shunt FACTS Devices in IEEE57 bus stressed system not only increase system loadability but also prevent voltage collapse.

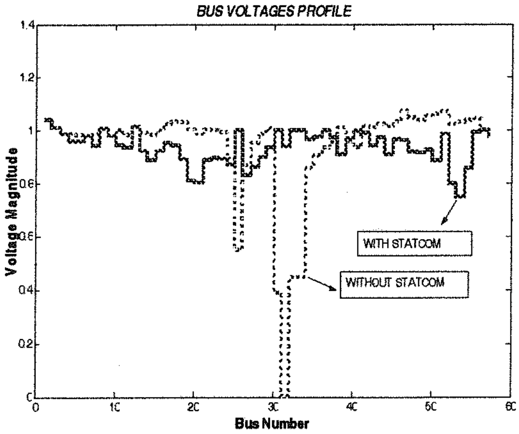

Figure 7: Bus voltage profile before and after allocation

Table 1 displays the results obtained by GA. In Table 1 we have presented rating and bus number of optimal placement STATCOM in IEEE57 bus test system (shown in Figure 9). In our simulation, the location and number of STATCOM's were obtained by GA, and the value of STATCOM's Mvar was determined by CPF method. Considering Table1 and Figure 9, one can find that almost all FACTS Devices are installed at weak buses from reactive power standpoint. A glance to Figure 9 indicates that these buses are far from reactive power source and hence are critical in voltage collapse phenomena.

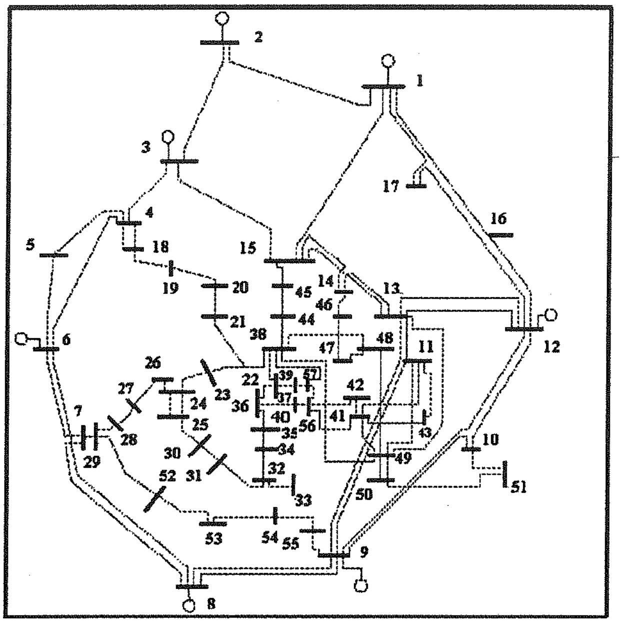

Figure 8: IEEE57 Bus Test System

TABLE 1

STATCOM placement (bus-Mvar-number)

Bus number	25	30	31	33	42	15
Mvar	7.8	9.8	5.6	15.3	8.16	50

Table 2 shows power system total loss before and after STATCOM installation. As seen from Table 1, optimal placement of STATCOM reduced power system total loss.

TABLE 2

STATCOM placement (bus-Mvar-number

Before STATCOM allocation	60.25 Mw
After STATCOM allocation	58.35 Mw
Percent of loss reduction	3.15%

5. CONCLUSION

We have presented simultaneously GA and CPF for optimal allocation of STSTCOM in a power system. The device is modeled for steady-state and transient stability studies. Optimizations were performed on three parameters, the number of the device, their location, and their value. The system loadability, improving bus voltage profile, and minimizing the power system losses were employed as measure of power system performance in optimization algorithm.

Simulations are done in both cases with generators Mvar limit and without generators Mvar limit. For all cases, power system loadability was increased. Moreover results have shown that the simultaneous use of GA and CPF are efficient solution to find the maximum system loadability and optimal placement of STATCOM. We observed a maximum number of STATCOM beyond

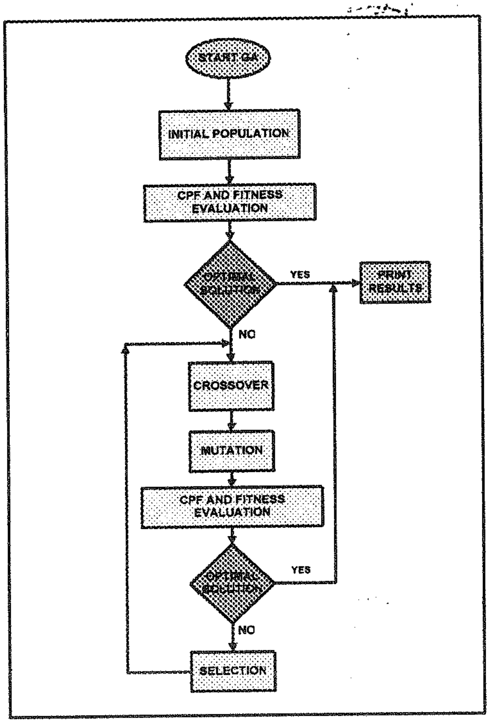

Figure 4: Fitness Function Evaluation Flowchart

Both GA and CPF are time consuming algorithms in the huge search space at simulation process. Our studies are in the planning stage; hence the accuracy and efficiency of results are more important than simulation time speed.

The goal of the optimization is to find the best location of a non-given number of FACTS devices in accordance with a defined criterion. A configuration of FACTS devices is defined with three parameters: the type, location and their values. In this paper, the type of device is given and hence, we are concerned on two other parameters. In order to take into account the two aforementioned parameters in the optimization, a particular coding is developed. An individual is represented with two strings length, the first contains the number of the STATCOM's to be located and the second string corresponds to the location of the device. It is important that GA can explore and generate all P-V bus candidates to STATCOM installation; hence we need an efficient genetic operator such as crossover and mutation to explore huge search space efficiently [17]. All simulation are done and repeated for confirmation and convergence of algorithm and in all case the simulation reached same results.

With optimal placement of STATCOM, it is possible to increase the system loadability. We found a maximum number of device beyond which the efficiency of the network cannot be further improved (Figure 5). It should be noticed that Figure 5 is a discrete response. According to the optimization criterion, for the tested power system, results show that this limit is about 10 devices for system with generators Mvar limit and about 7 for system without generators Mvar limit.

Figure 5 shows loading parameter λ, against STATCOM number with and without generators Mvar limit. Considering Figure 5, after optimal allocation of STATCOM maximum system loadability increased from base case $\lambda = 1$ to $\lambda = 1.64$ with generators Mvar limit and it increased to $\lambda = 1.84$ without generators Mvar limit, which λ is loading parameter. Results show that system loadability with generators Mvar limit is smaller with respect to case without generators Mvar limit.

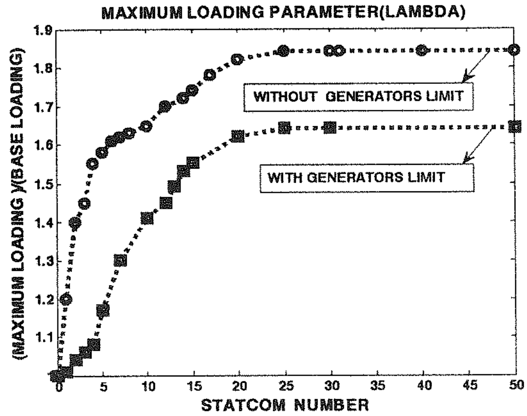

Figure 5: Number of STATCOM vs loading parameter

Figure 6 shows GA trace for placement of STATCOM for maximizing system loadability and improving bus voltage profiles and power system total loss. After 200 generation the GA simulation reached optimal solution. In Figure 7, we have shown P-V curves that indicate power system trajectory leading to stability margin and closing to voltage collapse phenomena in presence of STATCOM and without it. Figure 7 shows that using STATCOM maximum loadability of power system is considerably increased and static stability margin is improved.

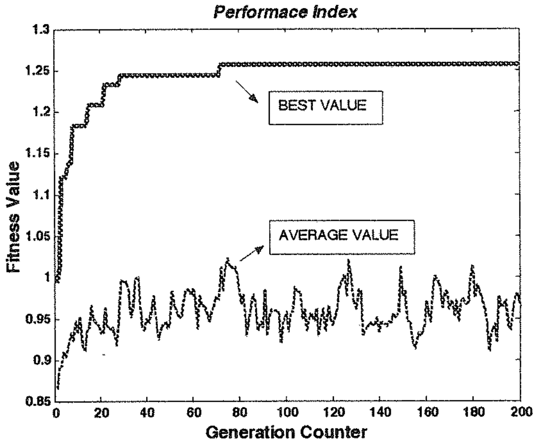

Figure 6: GA trace for placement of STATCOM

problem is transformed into a single objective optimization problem.

In general, the scalar fitness function for multi objective constraints optimization problem is as (8):

$$F(x) = \{ \ F_1(x), F_2(x), \dots, F_m(x) \dots \} \tag{8}$$

The functions $F_1(x), F_2(x), \dots$ and $F_m(x)$ are defined and used in optimization process. The optimization problem can be defined as (9) in which the fitness function includes constrained and unconstrained conditions.

$$\begin{aligned} &Minimize \quad F(x), Subject..to \\ &G_i(x) = 0 \quad i = 1,2,\dots,m_e \\ &G_i(x) \le 0 \quad i = m_e + 1,\dots,m \\ &x_l \le x \le x_u \end{aligned} \tag{9}$$

If we applied the coefficient of weighting factors ω_1, ω_2,... and ω_n to the problem such that $\sum_1^n \omega_i = 1$, the fitness function are determined from (10):

$$F = \omega_1 F^2{}_1 + \omega_2 F^2{}_2 + \dots + \omega_n F_n^2 \tag{10}$$

In our study, the fitness function is defined as a square sum of three terms with individual criteria. The first part of the objective function concerns on voltages level. It is favorable that buses voltages be close to 1 p.u as much as possible. The function is calculated for all buses of the power system. For voltage levels comprised between 0.95 p.u. and 1.05 p.u, the value of the objective function is equal to 1. Outside this range, the value decreases exponentially with the voltage deviation. Equations (11) and (12) depict the voltage deviation in all buses.

$$V_p = \exp\{[abs(1 - v_i) - dv]\} \tag{11}$$

$$F_V = \prod_{P=1}^{Bus\_number} V_p \tag{12}$$

where, V_i is voltage of bus i and dv is the voltage deviation from 1 pu. The second one is related to power system total loss and minimizing it in power system that are given with (13)-(14).

$$P_{Lk} = P_{sending} - P_{recieving} \tag{13}$$

$$F_L = P_{L\_total} = F_{loss} = \sum_{k=1}^{line\_number} P_{lk} \tag{14}$$

where P_{lk} indicates the loss in line ending to bus I and k, and $P_L = F_{loss}$ represents the total loss of power network.

From the power system static stability view, maximum loadability of power system is extremely important and, hence plays an important role in our study. Finally, the maximum loadability of power system is the third and important problem in our study that is as follows:

$$F_{SM} = F(X, Y, \lambda) = 1 - SM = 1 - \frac{1}{\lambda_{Crit}} \tag{15}$$

where, SM indicates the maximum stability margin of power system. When the power system is in normal state, $\lambda_{Crit} \to 1$, and SM going to one. With increasing loading parameter (λ), during the time, SM goes toward number zero.

In this paper objective function is given by (16):

$$F = \omega_1 F_V{}^2 + \omega_2 F_L{}^2 + \omega_3 F_{SM}^2 \tag{16}$$

where, functions F_V, F_L and F_{SM} are given by (12), (14) and (15) respectively. By substituting F_V, F_L and F_{SM} in (16) the objection function to maximizing in GA given as (17):

$$F = \frac{1}{\omega_1 \exp(F_{SM} - F_{SM0})^2 + \omega_2 \exp(F_V - F_{V0})^2 + \omega_3 \exp(F_L - F_{L0})^2} \tag{17}$$

where F_{V0}, F_{L0} and F_{SM0} are the values of voltages, power system total loss and maximum loading level in base case respectively. All of the variables are in pu and ω_1, ω_2, and ω_3 are chosen such that $\sum_1^n \omega_i = 1$.

B. Simulation Tools and Test System

Optimizations are carried out with a tool developed in MATLAB language. Simulations are performed on IEEE57 bus test power system. Generators are modeled as PV-node and loads as PQ-node with static behavior. The line is modeled using the classical scheme, valid for electrically short lines.

C. Optimization Strategy

As explained previously, the aim is to find the maximum amount of power system loadability that the power system is able to remain stable with an acceptable voltage level and reduced total loss. We look for locating STATCOM devices to increase the capability of the network as much as possible.

D. Simulation and Observed Results

In this section, for the clarity of our proposed technique the flowchart for combination of GA, CPF, predictor and corrector is illustrated in Figure 4.

the device is operating in the capacitive mode ($Q < 0$) and the negative sign for the inductive mode ($Q > 0$). The controller droop, X_{SL}, is directly represented in the V-I characteristic curve, with the controller limits being basically defined by its ac current limits $I_{\min}$ and $I_{\max}$. Furthermore, $V_{dc_{\max}}$ and $V_{dc_{\min}}$ are typically not an issue on steady state models.

3. LOADING PARAMETER AND CPF

A. Loading Parameter

The most accepted analytical tool used to investigate voltage collapse phenomena is the bifurcation theory which is a general mathematical theory that is able to classify instabilities. This theory is used for determining the system behavior in the neighborhood of collapse or unstable points and gives quantitative information on remedial actions to avoid critical conditions [11]. In the bifurcation theory, it is assumed that system equations depend on a set of parameters together with state variables, as (6):

$$\dot{x} = F(x,\lambda) = \lambda - x^2 \tag{6}$$

where, x represents power system state variable and λ is loading parameter. The stability or instability properties of system are assessed varying "slowly" the parameters such as λ. The parameter that was used to investigate system proximity to voltage collapse is called loading parameter, λ, which modifies load powers as follows:

$$\begin{aligned} P_{Li} &= (1 + k_{iP}\lambda)\, P_{L0i} \\ Q_{Li} &= (1 + k_{iq}\lambda)\, Q_{L0i} \end{aligned} \tag{7}$$

where P_0 and Q_0 are the active and reactive power at basic operating point at buses respectively, and k_1, k_2 are the control parameters to increase loading level. In typical bifurcation diagrams voltages are plotted as functions of λ, i.e. the measure of the system loadability, called P-V or nose curves. Equations (7) are used in continuation power flow analysis.

B. Continuation Power Flow (CPF)

Continuation Power Flow techniques is widely recognized as a valuable tool to determine nose curves of power systems and allow estimating the maximum loading conditions and "critical" solutions (for instance, saddle-node and limit induced bifurcation points). A graph of Continuation Power Flow is shown in Figure 3.

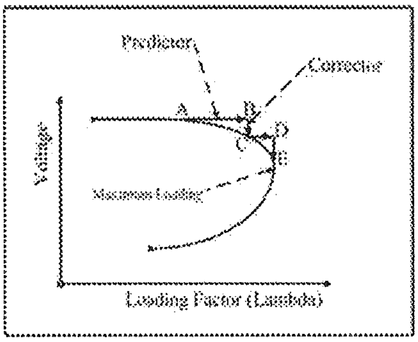

Figure 3: Continuation power flow illustration

CPF is not affected by numerical instabilities (it is able to determine the stable and unstable fold of P-V curves) and can provide additional information, such as sensitivity factors of the current solution with respect to relevant parameters [12]-[14].

From a mathematical point of view, the CPF is a homotopy technique [15] and allows exploring stability of power system equations when varying a system parameter, which, in typical static and dynamic voltage stability studies, is the loading parameter, λ, [16]-[17].

Generally speaking, CPF consists of predictor steps realized by the computation of the tangent vector and corrector step that can be obtained either by means of local parameterization or perpendicular intersection methods.

CPF technique uses an iterative process involving predictor and corrector step is shown in Figure 3.

Starting from a known initial point, A, a tangent predictor step is used to estimate the solution point B for a given load direction defined by λ. Then corrector step is used to determine the exact solution C using a power flow with an additional equation to find the proper value of λ. This process is repeated until the desired bifurcation diagram or P-V curve is obtained.

4. OBJECTIVE OF THE OPTIMIZATION

A. Definition of Fitness Function

The goal of the optimization is to perform a best utilization of the existing power network. In this respect, the FACTS devices are located in order to maximize the system loadability while observing thermal and voltage constraints. In other words, we look for increasing as much as possible the power transmitted by the network to the consumers, keeping the power system in a secure state in terms of maximizing loading level, minimizing power system total loss and flattening buses voltage. The objective function is built in order to optimize maximum loadability and minimizing over- or under-voltages at buses. Only the technical benefits of the STATCOM controller are taken into account. Other criteria such as costs of installing and maintaining are not taken into consideration at this stage of our research. As commonly done for multi-criteria constrained optimization, the simulation of Voltage Sourced Converter (VSC)-based controllers [4]-[7]. It is demonstrated here that the proposed model leads to accurate and reliable representing of STATCOM, operating in either phase or PWM control schemes, for voltage and angle stability studies uses in power flow, steady state and transient stability programs. This model allows an appropriate representation of the typical control limits for this controller [5]-[9].

2. STATCOM MODELS

There are several methods to describe STATCOM model in steady state and power flow studies such as power injection model and representing STATCOM as a synchronous condenser with zero active power output. In these conditions, controller represented as a reactive power source and usually control limits applied on reactive power. If the terminal voltage is known we can approximately determine the restrictions on controller current. The mentioned models for STATCOM do not have enough accuracy, because controller output voltage depends on the controller voltage's slope and STATCOM controlled bus [5]-[7] and [11].

The detailed model of STATCOM, based on an energy balance criterion depicted in (1). It is demonstrated here that the proposed model allows representing STATCOM in an accurate and reliabe way [6].

$$P = P_{dc} + P_l \tag{1}$$

That basically represents the balance between controller's ac power, P, and dc power, P_{dc}, under balanced operation at fundamental frequency. For more accuracy, it is important to represent the controller losses. Previously proposed models do not consider this issue.

Assuming balanced operation at fundamental frequency, the controller can be accurately modeled in transient stability studies. The transient stability model of a STATCOM is illustrated in Figure 1. The differential algebraic equations corresponding to this model can be readily written as follows:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \\ \dot{m} \end{bmatrix} = f_c(x_c, \alpha, m, V, V_{dc}, V_{ref}, V_{dc_{ref}}) \tag{2}$$

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta - \theta) - \frac{G_c}{C}V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}} \tag{3}$$

$$\begin{aligned} &P = VI\cos(\delta - \theta) \\ &Q = VI\sin(\delta - \theta) \\ &P = V^2G - KV_{dc}VG\cos(\delta - \alpha) - KV_{dc}VB\sin(\delta - \alpha) \\ &Q = -V^2B + KV_{dc}VB\cos(\delta - \alpha) - KV_{dc}VG\sin(\delta - \alpha) \end{aligned} \tag{4}$$

All of the variables are explained in Figures 1 and 2.

The admittance $G + jB = \frac{1}{R + jX}$ is used to represent the transformer impedance and any ac series filters (e.g, smoothing reactors), whereas G_c is used to model the "switching inertia" of the converter due to the electronic switches and their associated snubber circuits, which has a direct effect on the capacitor voltage dynamics. The constant $K = sqrt\ (3/8)m$ is directly proportional to the modulation index m.

The steady state or "power flow" model can be readily obtained from (2) by replacing the corresponding differential equations with the steady state equations of the dc voltage. Thus, the steady state equations for the PWM controller are as (5):

$$\begin{aligned} &V = V_{ref} \pm X_{SL}I \\ &V_{dc} = V_{dc_{ref}} \\ &P = G_cV_{dc}^2 + RI^2 \\ &P = VI\cos(\delta - \theta) \\ &Q = VI\sin(\delta - \theta) \\ &P = V^2G + KV_{dc}VG\cos(\delta - \alpha) - KV_{dc}VB\sin(\delta - \alpha) \\ &Q = -V^2B + KV_{dc}VB\cos(\delta - \alpha) - KV_{dc}VG\sin(\delta - \alpha) \end{aligned} \tag{5}$$

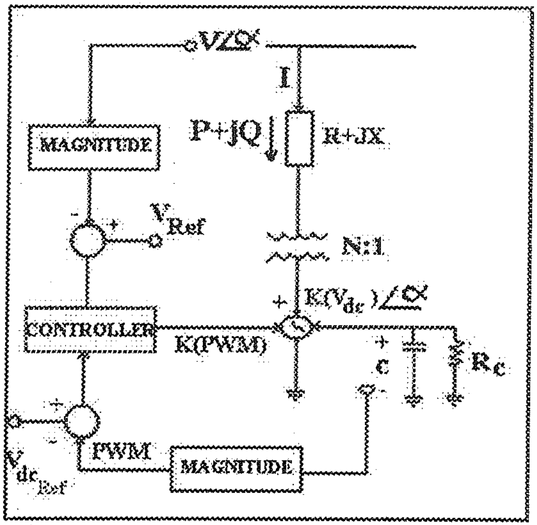

Figure 1: Transient stability model of a STATCOM

The voltage control characteristics of the STATCOM are shown in Figure 2.

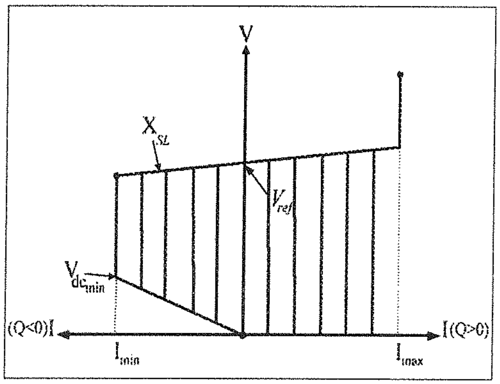

Figure 2: the V-I characteristics of STATCOM

In the first term of (5), the positive sign is used when

A New Method for Optimal Placement of Statcom Using Genetic Algorithms and Continuation Power Flow

S.R. Najafi[i]; S.H. Hosseinian[ii]; M. Abedi[iii]

ABSTRACT

This paper proposes a novel approach to determine optimal location of static synchronous compensator in power system for improving voltage profile, minimizing power system total loss and maximizing system loadability with and without considering generators Mvar limit. An accurate and efficient model for static synchronous compensator in steady state studies is presented and implemented in advanced load flow program with embedded flexible alternating current transmission systems. A simultaneous Genetic Algorithm and Continuation Power Flow was used to determine maximum number of static synchronous compensator's, and steady state stability margin, based on closing to point of voltage collapse. As an important result in this paper we obtain a maximum number of static synchronous compensator beyond which the power system performances such as loadability can not be increased, and hence, increasing loading level leads to static voltage collapse phenomena. A case study and simulation are done on IEEE57 Bus Test System. In Genetic Algorithm optimization procedure the voltage profile flattening, maximizing system loadability and minimizing total loss of power system are used as power system performance Index.

KEYWORDS

Bifurcation Theory, CPF, Genetic Algorithms, Loadability, STATCOM, Stability Margin, Voltage Collapse.

1. INTRODUCTION

Voltage collapse problems in power systems have been a permanent concern for power system as several major blackouts throughout the world have been directly associated to this phenomenon. The collapse points are also known as maximum loadability points. Increased loading of power system, environmental restrictions, combined with a world wide deregulation of the power industry, require more effective and efficient control means for power flow and stability control. The power flow control and static stability limits of power system can be considerably modified using the new reactive compensation equipments [1]-[2]. The development and use of Flexible AC Transmission System (FACTS) controllers in power transmission systems leads to optimal placement and applications of these controllers to improve bus voltage profile, stability of power networks and increasing power system loadability margin [3].

The STATCOM (STATic synchronous COMpensator) is a shunt connected reactive compensation equipment which is capable of generating and absorbing reactive power that its output can be varied so as to maintain control of specific parameters of electric power system [4]-[6].

Many studies have been carried out and reported in the literature on the use of these controllers for voltage and angle stability applications. A variety of optimizing techniques are used to optimal allocation of FACTS devices in power system. In [4] the author's used GA for optimal placement of multiple choice FACTS controllers to improve buses voltage profile. In mentioned paper FACTS devices are described with simplified reactance model and the fitness function only involved bus voltage flattening and lines loading level.

Several distinct models have been proposed to represent FACTS in static and dynamic analysis [3]. The current paper concentrates on describing STATCOM model for these types of studies in detail, based on an energy balance criterion used in the modeling and

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