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# Optimal Allocation of TCSC Device Based on Particle Swarm Optimization Algorithm

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## Abstract

*This paper presents an application of Particle Swarm Optimization (PSO) to find out the optimal location and the optimal parameter settings of TCSC devices under single contingency to eliminate the bus voltage violations and improvement of power flow in a transmission line. The particle swarm optimization (PSO) technique is used to solve the optimal power flow problem for steady-state studies by maintaining thermal and voltage constraints. The suitability of the proposed approach is examined on the standard IEEE 30-bus test system with TCSC FACTS device. Simulation results show that proposed PSO algorithm gives better solution to enhance the system performance with TCSC device compared to without TCSC FACTS device.*

**Keywords**: Newton Raphson's Method, TCSC, FACTS device, Particle Swarm Optimization (PSO) technique, Optimal Power Flow, Cost of Generation.

## 1. Introduction

The operation mechanism of power system becomes more and more complicated due to the continuously increasing load demand which leads to an augmented stress of the transmission lines and higher risks for faulted lines. Therefore, power system can be operated in less secure state following unexpected line congestions and low voltages. Construction of new transmission lines can be one solution for leading more stable and secure operation of power systems. But it becomes a time-consuming process due to political and environmental reasons. Because of all that, it becomes more important to control the power flow along the transmission lines to meet the needs of power transfer [1]-[2].

Power flow is a function of transmission line impedance, the magnitude of the sending end and receiving end voltages and the phase angle between voltages. By controlling one or a combination of the power flow arrangements, it is possible to control the active as well as the reactive power flow in the transmission line [3].

A new solution to improve the stability and security of the power system is the Flexible AC Transmission Systems FACTS devices [4] can improve the stability of the power network, reduce the flows of heavily loaded lines by controlling their parameters,

and maintain the bus voltages at desired level. Consequently they can improve the power system security in contingency [5].

With FACTS technology [6]-[7] , such as Thyristor Controlled Series Compensator (TCSC), Static Var

Compensators (SVCs), Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controller (UPFC) etc ,bus voltages, line impedances and phase angles in the power system can be regulated rapidly and flexibly. Thus, FACTS can facilitate the power flow control, enhance the power transfer capability, decrease the generation cost, and improve the security and stability of the power system.

Thyristor Controlled Series Compensator (TCSC) is one of the most effective FACTS devices which offer smooth and flexible control of the line impedance with much faster response [8]. TCSC can also enhance the transient stability of power system that means if there is any sudden change of load that occurs in power system it will maintain stability without loss of synchronism by using TCSC FACTS device is connected in series with the transmission line and also increase the transfer capability of the transmission system by reducing the transfer reactance between the buses at which the line is connected. However, to achieve the above mentioned benefits, the TCSC should be properly installed in the network with appropriate parameter settings [9]

Thus in this paper, TCSC FACTS controller is incorporated to solve an optimization problem with different objectives such as minimization of cost of generation, real power loss, enhancement of voltage profile and voltage angles and L-index as these are the basis for improved system performance. The particle swarm optimization (PSO) based algorithm is used effectively to solve the optimal power flow problem [10], it present great characteristics and capability of determining global optima, incorporating a set of constraints including voltage stability and FACTS device. In order to calculate the power losses and check the system operating constraints such as voltage profile, a load flow model is used. An existing Newton-Rapson load flow algorithm is introduced [11]. This model is further modified to incorporate TCSC FACTS device into the network and PSO technique is applied to the modified model to enhance the performance of the power system. Thus, effectiveness of the proposed method was tested on standard IEEE 30-bus system and comparison was made on the performance of without and with TCSC FACTS device.

The organization of this paper is as follows. Section 2 addresses the Computation of Voltage Stability Index (L-index), FACTS controller such as TCSC is explained in Section 3, Mathematical formulation of OPF problem is given in section 4, Overview of Particle Swarm Optimization Algorithm is represented in section 5, Overall Computational Procedure is given in the section 6, the simulation results is given in section 7, and Comparison of fuel cost of generation with different OPF models is illustrated in section 8, and finally the conclusion is given in section 9.

## 2. Voltage Stability Index (L-index) Computation

The voltage stability L-index is a good voltage stability indicator with its value change between zero (no load) and one (voltage collapse) [5]-[6]. Moreover, it can be used as a quantitative measure to estimate the voltage stability margin against the operating point. For a given system operating condition, using the load flow (state estimation) results, the voltage stability $L$-index is computed as [5],

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \qquad (1)$$

$$j = g+1, \ldots, n$$

All the terms within the sigma on the RHS of equation (1) are complex quantities. The values of $\boldsymbol{F}_{ji}$ are btained from the network *Y*-bus matrix. For stability, the index $L_j$ must not be violated (maximum limit=1) for any of the nodes j. Hence, the global indicator $L_j$ describing the stability of the complete subsystem is given by maximum of $\mathrm{L}_j$ for all $j$ (load buses). An $L_j$-index value away from 1 and close to 0 indicates an improved system security. The advantage of this $L_j$-index lies in the simplicity of the numerical calculation and expressiveness of the results.

## 3. FACTS controllers

FACTS controllers are able to change, in a fast and effective way, the network parameters in order to achieve better system performance. FACTS controllers such as phase shifter, shunt, or series compensation and the most recent developed thyristor controlled based power electronic controllers, make it possible to control circuit impedance, voltage angle and power flow for optimal operation performance of power systems, facilitate the development of competitive electric energy markets, stimulate the unbundling the power generation from transmission and mandate open access to transmission services, etc. The benefit brought about by FACTS includes improvement of system behavior and enhancement of system reliability. However, their main function is to control power flows.

### 3.1. Thyristor Control series Compensator (TCSC)

One of the important FACTS controllers is the TCSC which allows rapid and continuous changes of the transmission line impedance. TCSC [14]-[16] controls the active power transmitted by varying the effective line reactance by connecting a variable reactance in series with line and is shown in Figure 1. TCSC is mainly used for improving the active power flow across the transmission line.

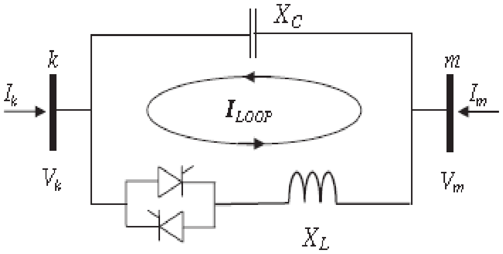

**Figure 1. Circuit diagram of TCSC**

The active and reactive power equations at bus *k* are:

$$P_k = V_k V_m B_{km} \sin(\theta_k - \theta_m) \qquad (2)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m) \qquad (3)$$

For the power equations at bus *m*, the subscripts *k* and *m* are exchanged in Equations (2) and (3).

In Newton-Raphson solutions these equations are linearized with respect to the series reactance. For the condition, where the series reactance regulates the amount of active power flowing from bus *k* to bus *m* at a value $P_{km}^{reg}$, the set of linearized power flow equations is

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{X_{TCSC}} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial X_{TCSC}} X_{TCSC} \\ \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_k} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial \theta_m} & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_k} V_k & \frac{\partial P_{km}^{X_{TCSC}}}{\partial V_m} V_m & \frac{\partial P_{km}^{X_{TCSC}}}{\partial X_{TCSC}} X_{TCSC} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \frac{\Delta X_{TCSC}}{X_{TCSC}} \end{bmatrix} \tag{4}$$

Where $\Delta P_{km}^{TCSC}$ is the active power flow mismatch for the series reactance

$$\Delta P_{km}^{TCSC} = P_{km}^{reg} - P_{km}^{X_{TCSC,cal}}$$

$\Delta X_{TCSC}$ is given as

$$\Delta X_{TCSC} = X_{TCSC}^{i} - X_{TCSC}^{i-1}$$

and is the incremental change in series reactance; and $P_{km}^{X_{TCSC,cal}}$ is the calculated power.

The state variable $X_{TCSC}$ of the series controller is updated at the end of each iterative step according to

$$X_{TCSC}^{(i)} = X_{TCSC}^{(i-1)} + \left( \frac{\Delta X_{TCSC}}{X_{TCSC}} \right)^{(i)} X_{TCSC}^{(i-1)} \tag{5}$$

This changing reactance represents the series reactance regulates the amount of active power flowing from bus *k* to bus *m* at a specified value $P_{km}^{reg}$

## 4. Mathematical formulation of OPF Problem

Mathematically, the OPF problem with FACTS is solved to minimize fuel cost of generation maintaining thermal and voltage constraints can be formulated as follows [17]-[18]:

$$\text{Minimize } F = \left(\sum_{i=1}^{NG} (a_i P_{Gi}^2 + b_i P_{Gi} + C_i\right) \tag{6}$$

The minimization problem is subjected to following equality and inequality constraints

### 4.1 Equality Constraints

These are the sets of nonlinear power flow equations that govern the power system, i.e.

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{7}$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{8}$$

Where $P_{Gi}$ and $Q_{Gi}$ are the real and reactive power outputs injected at bus $i$, the load demand at the same bus is represented by $P_{Di}$ and $Q_{Di}$, and elements of the bus admittance matrix are represented by $|Y_{ij}|$ and $\theta_{ij}$.

### 4.2 Inequality Constraints

These are the set of constraints that represent the system operational and security limits like the bounds on the following:

1) Generators real and reactive power outputs

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1, \ldots, N \tag{9}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1, \ldots, N \tag{10}$$

2) Voltage magnitudes at each bus in the network

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1, \ldots, NL \tag{11}$$

3) Transformer taps setting

$$T_i^{\min} \le T_i \le T_i^{\max}, i = 1, \ldots, NT \tag{12}$$

4) Reactive power injections due to capacitor banks

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max}, i = 1, \ldots, CS \tag{13}$$

5) Transmission lines loading

$$S_i \le S_i^{\max}, i = 1, \ldots, nl \tag{14}$$

6) Voltage stability index

$$Lj_i \le Lj_i^{\max}, i = 1, \ldots, NL \tag{15}$$

7) TCSC device constraints:

Reactance constraint of TCSC

$$X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \tag{16}$$

The equality constraints are satisfied by running the power flow program. The generator bus real power generations ($P_{gi}$), generator terminal voltages ($V_{gi}$), transformer tap settings ($T_i$), the reactive power generation of capacitor bank ($Q_{Ci}$), and $P_{km}^{reg}$ of TCSC are control variables and they are self-restricted by the representation itself. The active power generation at the slack bus ($P_{gs}$), load bus voltages ($V_{Li}$) and reactive power generation ($Q_{gi}$), line flows ($S_i$), and voltage stability ($L_j$)-index are state variables which are restricted through penalty function approach.

## 5. Overview of Particle Swarm Optimization

PSO is one of the optimization techniques and belongs to evolutionary computation techniques [19]. PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each individual (agent) is represented by XY axis position Modification of the agent position is realized by the position and velocity information.

An optimization technique based on the above concept can be described as follows: namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value so far in the group (gbest) among pbests [20]. Each agent tries to modify its position. This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$v_i^{k+1} = wv_i^k + c_1 rand_1 * (pbest_i - s_i^k) + c_2 rand_2 * (gbest - s_i^k) \tag{17}$$

Where, $v_i^k$ : Velocity of agent i at iteration k,

$w$ : weighting factor,

$c_1$ & $c_2$: cognition and social components,

rand: random number between 0 and 1

$s_i^k$ : Current position of agent i at iteration k.

$\text{pbest}_i$ : the pbest of agent i.

gbest : gbest of group.

Using the above equation, a certain velocity which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{18}$$

## 6. Overall Computational Procedure for Solving the Problem

The implementation steps of the proposed PSO based algorithm can be written as follows;

Step 1: Input the system data for load flow analysis

Step 2: Select FACTS devices and its location in the system

Step 3: At the generation Gen =0; set the simulation parameters of PSO parameters and randomly initialize k individuals within respective limits and save them in the archive.

Step 4: For each individual in the archive, run power flow under the selected network contingency to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.

Step 5: Evaluate the penalty functions

Step 6: Evaluate the objective function values and the corresponding fitness values for each individual.

Step 7: Find the generation local best xlocal and global best xglobal and store them.

Step 8: Increase the generation counter Gen= Gen+1.

Step 9: Apply the PSO operators to generate new k individuals

Step 10: For each new individual in the archive, run power flow to determine load bus voltages, angles, load bus voltage stability indices, generator reactive power outputs and calculate line power flows.

Step 11: Evaluate the penalty functions

Step 12: Evaluate the objective function values and the corresponding fitness values for each new individual.

Step 13: Apply the selection operator of PSO and update the individuals.

Step 14: Update the generation local best **xlocal** and global best **xglobal** and store them.

Step 15: If one of stopping criterion have not been met, repeat steps 4-14. Else go to stop 16

Step 16: Print the results

## 7. Simulation Results

The proposed PSO algorithm is employed to solve optimal power flow problem incorporating TCSC FACTS device for enhancement of system

Performance is tested on standard IEEE 30-bus test system.

The PSO parameters used for the simulation are summarized in Table 1

**Table 1. Optimal parameter settings for PSO**

| Parameter | PSO |
|---|---|
| Population size | 20 |
| Number of iterations | 150 |
| Cognitive constant, c1 | 2 |
| Social constant, c2 | 2 |
| Inertia weight, W | 0.3-0.95 |

The network and load data for this system is taken from [21]. To test the ability of the proposed PSO algorithm one objective function is considered that is minimization of cost of generation. In order to show the affect of power flow control capability of the

FACTS device in proposed PSO OPF algorithm, two sub case studies are carried out on the standard IEEE 30-bus system.

Case (a):power system normal operation (without FACTS devices installation),

Case (b): One TCSC device is installed at an optimal line connected between buses 9 and 10 with line real power flow $P_{ji}$ is $\pm$ 1.25 times of base case values.

The series reactance ( $X_{TCSC}$ ) ratings of TCSC is set at 50% of the transmission-line, thus inductive Reactance is 0.055.

The first case is the normal operation of network without using any FACTS device, in second case optimal location of one TCSC device has been considered.

From Table 2. it shows that the details of the control variables and the installation of TCSC in the network gives the best performance of the system compared to the without FACTS device in the network in terms of reduction in cost of generation, power loss reduction, maximum of voltage stability indices. It also gives that PSO algorithm is able to enhance the system performance while maintaining all control variables and reactive power outputs within their limits

The convergence characteristic of the cost of generation without and with TCSC (one at a time) at optimal location is shown in figure 2

**Table 2. Optimal settings of control variables for IEEE 30- bus system.**

| Control Variables | Limits(p.u) | | Without FACTS | With FACTS |
|---|---|---|---|---|
| | Min | Max | | TCSC |
| $P_{G1}$ | 0.50 | 2.000 | 1.7718 | 1.7748 |
| $P_{G2}$ | 0.20 | 0.800 | 0.4867 | 0.4888 |
| $P_{G3}$ | 0.10 | 0.350 | 0.2109 | 0.2080 |
| $P_{G4}$ | 0.10 | 0.300 | 0.1215 | 0.1183 |
| $P_{G5}$ | 0.15 | 0.500 | 0.2144 | 0.2147 |
| $P_{G6}$ | 0.12 | 0.400 | 0.1200 | 0.1202 |
| $V_{G1}$ | 0.95 | 1.10 | 1.0868 | 1.0854 |
| $V_{G2}$ | 0.95 | 1.10 | 1.0667 | 1.0656 |
| $V_{G3}$ | 0.95 | 1.10 | 1.0405 | 1.0382 |
| $V_{G4}$ | 0.95 | 1.10 | 1.0645 | 1.0369 |
| $V_{G5}$ | 0.95 | 1.10 | 1.0348 | 1.0338 |
| $V_{G6}$ | 0.95 | 1.10 | 1.0425 | 1.0442 |
| Tap - 1 | 0.9 | 1.1 | 1.0464 | 1.0114 |
| Tap - 2 | 0.9 | 1.1 | 0.9000 | 1.0187 |
| Tap - 3 | 0.9 | 1.1 | 0.9568 | 0.9651 |
| Tap - 4 | 0.9 | 1.1 | 0.9623 | 0.9831 |
| $Q_{C10}$ | 0.0 | 0.10 | 0.0783 | 0.0993 |
| $Q_{C12}$ | 0.0 | 0.10 | 0.0000 | 0.0000 |
| $Q_{C15}$ | 0.0 | 0.10 | 0.0629 | 0.0264 |
| $Q_{C17}$ | 0.0 | 0.10 | 0.0518 | 0.0276 |
| $Q_{C20}$ | 0.0 | 0.10 | 0.0785 | 0.0666 |
| $Q_{C21}$ | 0.0 | 0.10 | 0.0386 | 0.0693 |
| $Q_{C23}$ | 0.0 | 0.10 | 0.0429 | 0.0337 |
| $Q_{C24}$ | 0.0 | 0.10 | 0.0260 | 0.0415 |
| $Q_{C29}$ | 0.0 | 0.10 | 0.0260 | 0.0336 |
| Cost ($/h) | | | 800.8678 | 800.5671 |
| Ploss (p.u.) | | | 0.0913 | 0.0904 |
| Ljmax | | | 0.1381 | 0.1301 |
| CPU time (s) | | | 45.5510 | 53.8600 |

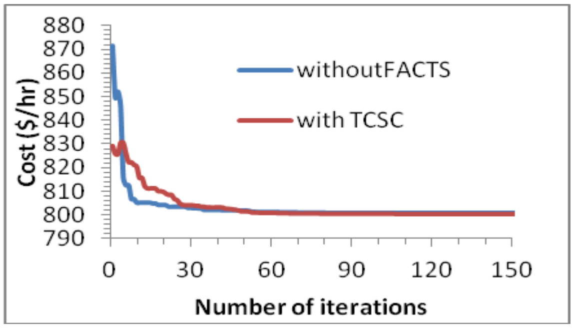

**Figure 2. Convergence of cost of generation without and with TCSC FACTS device for IEEE 30-bus system**

The Figures 3-6 shows the percentage MVA loading of the lines, voltage profiles, voltage angles, and voltage stability indices of buses without and with TCSC at optimal location

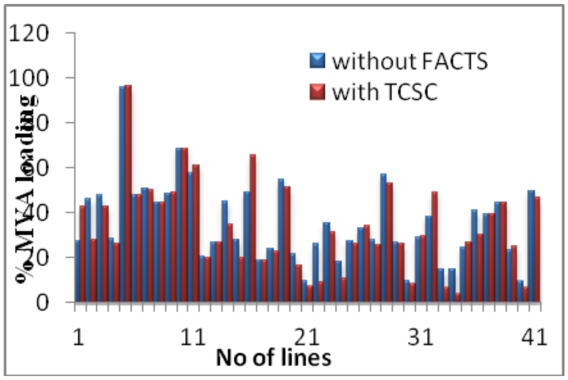

**Figure 3. Percentage MVA line loadings of IEEE 30-bus system after optimization without FACTS and with TCSC FACTS device**

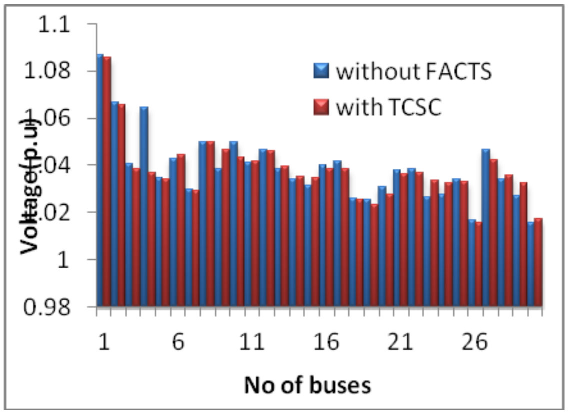

**Figure 4. Voltage profiles of IEEE 30-bus system after optimization without and with TCSC FACTS device.**

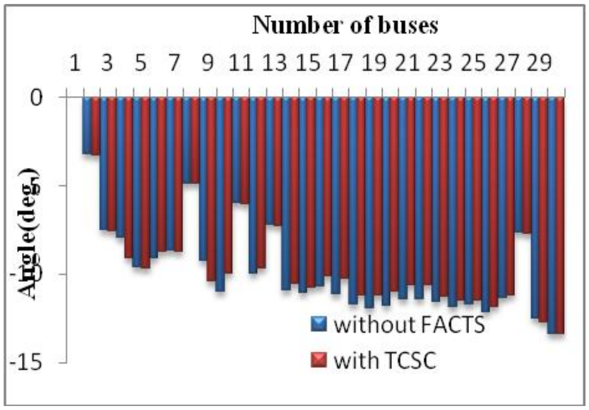

**Figure 5. Voltage angles of IEEE 30-bus system after optimization without and with TCSC FACTS device.**

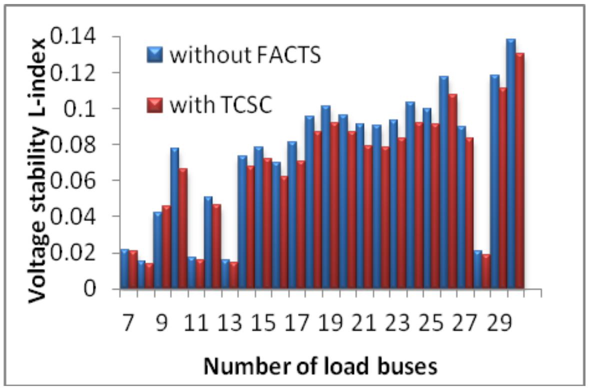

**Figure 6. Voltage stability indices of IEEE 30-bus system after optimization without and with TCSC FACTS device**

## 8. Comparison of fuel cost of generation with different OPF models

The comparison of fuel cost of the proposed method with those of the methods reported in the literature is given in Table 3. It can be seen that PSO algorithm gives less cost of generation compared with the cost of generation obtained with other OPF methods.

**Table 3. Comparison of fuel costs for IEEE 30-bus System**

| **Method** | **Fuel Cost ($/hr)** |
|---|---|
| EP [22] | 802.907 |
| TS [23] | 802.502 |
| TS/SA [23] | 802.788 |
| ITS [24] | 804.556 |
| IEP [25] | 802.465 |
| SADE_ALM [26] | 802.404 |
| OPFPSO [19] | 800.410 |
| MDE-OPF [27] | 802.376 |
| Genetic Algorithm ($/hr) [28] | 803.050 |
| Gradient method [29] | 802.430 |
| PSO (proposed) without FACTS | 800.8678 |
| PSO (proposed) with TCSC | 800.5600 |

From Table 3 It can be seen that the PSO algorithm with TCSC gives less cost of generation compared with the cost of generation obtained with other OPF methods

## 9. Conclusions

This paper has presented an OPF model incorporating FACTS controller such TCSC using the PSO algorithm for enhancement of system performance. This model is able to solve power networks of any size and converges with minimum number of iterations and independent of initial conditions. The standard IEEE 30-bus system has been used to demonstrate the proposed method over a wide range of power flow variations in the transmission system. The simulation results shows that proposed OPF with thyristor Controlled Series Compensator (TCSC) scheme is very effective compared to without FACTS in improving the security of the power system.

- TCSC FACTS device can increases the power transfer capability of the transmission line by increasing the voltage at their terminals of both ends of transmission line and also decrease the line reactance for improving power transfer capability.
- Proper selection of FACTS device and its location can effectively improve the overall system performance.
- Finally, the optimization problem with different objectives such as minimization of cost of generation, reduction in power loss, enhancement of voltage profile and voltage angle at every bus and L-index are improved system performance

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