# Thyristor Controlled Series Capacitor For Generation Reallocation Using Firefly Algorithm to Avoid Voltage Instability

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**ABSTRACT:**
Modern electric power utilities are facing many challenges due to increasing complexity in their operation and structure. In the recent times, one of the problems that got wide attention is the power system instabilities due to lack of new transmission facilities. Existing transmission facilities can be better utilized by installing Flexible AC Transmission System (FACTS) devices. The Thyristor Controlled Series Capacitor (TCSC) is the most effective FACTS device used to increase the power transferable capabilities of the transmission line. This paper presents a sensitivity analysis based on Complex Power Flow Sensitivity Index (CPSI) calculation for placing the TCSC at an appropriate location. Once the location for installing the TCSC is determined, the optimal tuning of the TCSC and the impact of TCSC on generation reallocation is determined through Firefly Algorithm. This Algorithm was implemented on multi objective function to obtain the Optimal Power Flow. The multi objective function consists of total real power loss, total voltage magnitude deviations, the fuel cost of total real power generation and the branch loading. Simulations have been carried out in MATLAB environment for the IEEE 57-bus system. The results have been taken for Firefly Algorithm based Optimal Power Flow without and with TCSC. The results obtained with Firefly Algorithm were compared with Genetic Algorithm (GA).

**KEYWORDS:** Firefly Algorithm, Optimal placement, Sensitivity index, TCSC.

## 1. INTRODUCTION

Modern electric power utilities are facing many problems due to increasing complexity in their operation and structure. In recent years, the transmission lines are operated under the heavily stressed condition, hence there is a risk of consequent voltage instability in the power network. Conventional power systems are controlled mechanically [1], [2]. Mechanical devices are inferior to static devices as they tend to wear out quickly. This necessitates power flow control to shift from mechanical devices to static devices. Static devices called the Flexible Alternating Current Transmission System (FACTS) device [3] were developed, capable of effectively controlling the load flow distribution and the power transfer capability. The FACTS device performance depends upon its location and parameter setting. The power electronic based FACTS introduced in 1980's, provided a highly efficient and economical means to control the power transfer in interconnected AC transmission systems [4]. Power flow through an AC line is a function of phase angles, bus voltages and line impedance. Using FACTS devices, these variables can be effectively and efficiently controlled. A FACTS device in a power system improves voltage stability, reduces the power loss and also improves the stability of the system. However, controlling power flow is the main function of FACTS device [5], [6].

Although several methods were suggested in literature to protect power system networks against voltage collapse, the placement of FACTS controllers has been established as an effective means. However, due to high cost of the FACTS devices, it is important to optimally place these controllers in the system. The Thyristor Controlled Series Capacitor (TCSC) is one of the most effective Flexible AC Transmission System devices. It regulates the power flow through the transmission line. Many authors have found the use of TCSC. The TCSC is used to damp power oscillations and to improve the transient stability of power systems. The optimal placement of Thyristor Controlled Series Compensators in transmission systems is formulated as a multi-objective optimization problem to minimize the losses [7], [8].

This paper presents a Sensitivity analysis based on Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at appropriate location. A new metaheuristic optimization technique called the Firefly algorithm is introduced to find the optimal size of the TCSC device and also for generation reallocation to improve stability. Its performance is compared with the Genetic Algorithm (GA) technique. The real and reactive power generation values and bus voltage limits for generator buses are taken as constraints, along with reactance limits of the TCSC, during the optimization. Computer simulations using MATLAB were done for the IEEE 57 bus system. In this paper, a new line-based voltage stability index is proposed to evaluate the stability condition in a power system.

## 2. PROBLEM FORMULATION

In this paper, a multi objective function is formulated, to find optimal size of the TCSC device by minimizing certain objective functions subject to network constraints. The multi-objective problem can be written mathematically as follows,

### 2.1. Objective function

For a given system load, we look for the best configuration of TCSC device and generation reallocation by minimizing the following objective function:

$$\mathrm{Min}(F) = \min(W_1 * FC + W_2 * F_{Ploss} + W_3 * F_{VD} + W_4 * F_S) \quad (1)$$

Where $W_1$, $W_2$, $W_3$, $W_4$ are the weighting factors $W_1 + W_2 + W_3 + W_4 = 1$

$W_1 = W_2 = W_3 = W_4 = 0.25$

Reactance of TCSC has been added as a control variable along with real power generation of the generator buses for optimization problem. TCSC limits are given as:

$$X_{TCSC}^{min} \leq X_{TCSC} \leq X_{TCSC}^{max} \quad (2)$$

- *Fuel cost:*

The objective function considering the minimization of total real power generation cost can be represented by following quadratic equation

$$FC = \min\left(\sum_{i=1}^{ng} a_i P_{Gi}^2 + b_i P_{Gi} + c_i\right) \quad (3)$$

here ng = no. of the generator buses

a, b, c are the fuel cost coefficients of a generator unit

- *Active Power Loss:*

The objective of this function is to minimize real power losses in the transmission lines. It can be expressed as

$$F_{PLoss} = \min\left(\sum_{k=1}^{ntl} \mathrm{real}\,(S_{ij}^k + S_{ji}^k)\right) \quad (4)$$

Where ntl=no. Of the transmission lines

$S_{ij}$ is the total complex power, flows from bus i to bus j in line k.

- *Voltage Deviation:*

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. The Voltage Deviation (VD) can be expressed as:

$$F_{VD} = \min(VD) = \min\left(\sum_{k=1}^{N} |V_k - V_k^{ref}|^2\right) \quad (5)$$

$V_k$ is the voltage magnitude at bus k

$V_k^{ref}$ is the reference voltage magnitude at bus k

N is the number of buses

- *Branch loading:*

The goal of minimizing the branch loading in the transmission lines is to enhance the security level of the system. It can be expressed as

$$F_S = \min(S) = \min\left(\sum_{k=1}^{ntl}\left(\frac{|S_k|}{|S_k^{max}|}\right)^2\right) \quad (6)$$

$S_k$ is the apparent power in line k and $S_k^{max}$ is the maximum apparent power in line k.

- *Equality constraints:*

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + P_L \quad (7)$$

Where i=1,2,3,.......,N and N = no. of the Buses

$$\sum_{i=1}^{N} Q_{Gi} = \sum_{i=1}^{N} Q_{Di} + Q_L \quad (8)$$

Where i=1,2,3,.......,N and N = no. of the buses

$P_L$ is total active power losses

$Q_L$ is total reactive power losses

- *Inequality constraints:*
  - *Generator bus Voltage limits:*

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max} \quad (9)$$

Where i=1,2,3,.......,N and N = no.of the buses

  - *Real power generation limit:*

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (10)$$

Where i=1,2,3,......,ng and ng= no.of the generator buses

  - *Reactive Powergeneration limits:*

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (11)$$

### 2.2. Fast Voltage Stability Index (FVSI)

Several techniques were proposed to analyse the static voltage stability condition in a system. Some of them were utilized the voltage stability indices referred either to a bus or to a line as an indicator to voltage collapse. In this paper, a new line-based voltage stability index is implemented to evaluate the line stability condition in a power system. This index is called as Fast Voltage Stability Index (FVSI). The system becomes unstable if FVSI is equal to or greater than unity.

FVSI can be expressed as

$$FVSI_{ij} = \frac{4 Z^2 Q_j}{V_i^2 X} \quad (12)$$

Where Z is the line impedance

X is the line reactance

Qj is the reactive power at bus j (receiving end bus)

Vi is the voltage magnitude at bus i (sending end bus)

FVSI value of any line close to unity indicates that the system is prone to voltage collapse. Therefore, FVSI has to be maintained less than unity in order to maintain a stable system.

## 3. THYRISTOR CONTROLLED SERIES CAPACITOR

Thyristor controlled series capacitor (TCSC) controller consists of a series capacitor paralleled by a thyristor-controlled reactor in order to provide smooth variable series compensation. The basic Thyristor-controlled series capacitor scheme was proposed in 1986 by Vithaythil along with others. Apart from enhancing system stability, the TCSC also increases the line power transfer capability. The basic module of a TCSC is shown in Fig. 1. It consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors. Thyristor inhibition in the TCSC module enables it to have a smoother control over its reactance in response to system parameter variations [9, 10].

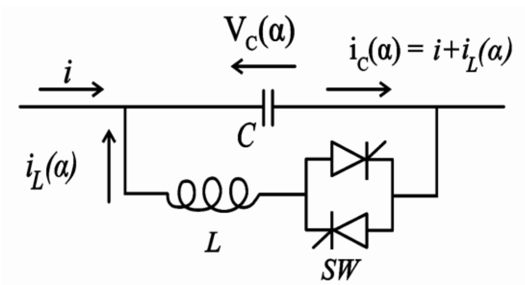


**Fig.1**. Basic TCSC model

$X_C$ = fixed capacitive impedance
$X_L$ = variable inductive impedance

$$X_{TCSC} = \frac{X_C X_L}{X_L - X_C} \tag{13}$$

Where $X_{TCSC}$ = reactance of TCSC

However, it may be argued that the primary function of the TCSC is to reduce the electrical length of the compensated transmission line. So as to increase power transfers significantly with increased transient stability margins. The TCSC power flow model presented in this section is based on the simple concept of a variable series reactance, the value of which is adjusted automatically in order to constraint the power flow across the branch is specified [11, 12]. The amount of reactance is determined efficiently using Firefly Algorithm. The changing reactance $X_{TCSC}$, shown in Figure 2, represents the equivalent reactance of all the series-connected modules making up the TCSC, when operating in either the inductive or the capacitive regions [13], [14].

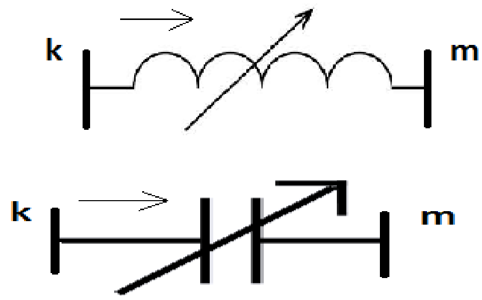


**Fig. 2.** Thyristor-controlled series capacitor equivalent circuit: Inductive and capacitive operative regions

The transfer admittance matrix of the variable series compensator shown in Figure 2 is given by

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \tag{14}$$

For capacitive operation, we have

$$B_{kk} = B_{mm} = \frac{1}{X_{TCSC}} \tag{15}$$

$$B_{km} = B_{mk} = -\frac{1}{X_{TCSC}} \tag{16}$$

For inductive operation the signs are reversed

The active and reactive power equations at bus k are:

$$P_k = V_k V_m B_{km} \sin(\theta_k - \theta_m) \tag{17}$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m) \tag{18}$$

Where $\theta_k$ = phase angle at bus k.

$\theta_m$ = phase angle at bus m.

The series reactance regulates the amount of active power flowing from bus k to bus m. The change in reactance of TCSC is

$$\Delta X_{TCSC} = X_{TCSC}^{i} - X_{TCSC}^{(i-1)} \tag{19}$$

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

$$X_{TCSC}^{i} = X_{TCSC}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right) X_{TCSC}^{(i-1)} \tag{20}$$

$X_{TCSC}^{i}$ is the reactance of TCSC at $i^{th}$ iteration.

$X_{TCSC}^{(i-1)}$ is the reactance of TCSC at $(i\text{-}1)^{th}$ iteration.

## 4. COMPLEX POWER FLOW SENSITIVITY INDEX FOR OPTIMAL PLACEMENT OF TCSC

A method based on the sensitivity, the sum of variations of complex power flow in all lines with respect to the change of reactance of a line is proposed. The TCSC has been modelled as a variable series reactance $X_{TCSC}$. By installing TCSC in line which may decrease or increase the total line reactance. The index is computed using Newton Raphson power flow. CPSI at a line j is given as:

$$\mathrm{CPSI_j} = \sum_{n=1}^{ntl} \left(\frac{\Delta S_n}{\Delta X_j}\right) \quad (21)$$

Where n=1, 2, 3,......., ntl and ntl = no.of the transmission lines.
$\Delta S_n$ is change in complex power flow in line n
$\Delta X_j$ is change in reactance of the line j

This index is calculated for all the lines. The minimum and maximum values of CPSI are obtained. Normalized complex power flow sensitivity index is defined as:

$$\mathrm{CPSI_n}(j) = \frac{\mathrm{CPSI_j} - \mathrm{CPSI_{min}}}{\mathrm{CPSI_{max}} - \mathrm{CPSI_{min}}} \quad (22)$$

Where $\mathrm{CPSI_n}(j)$ is the normalized complex power flow sensitivity index at line j.
Highest normalized complex power flow sensitivity index is the best location for placement of TCSC. From the Table I it is observed that highest positive value of $\mathrm{CPSI_n}(j)$ is 1 for line number 76 and TCSC is placed in line number 76. Complex power flow sensitivity Index values for all lines in the IEEE 57 bus system are given in Table 1.

**Table 1**. Complex power flow sensitivity Index values for all lines in the IEEE 57 bus system

| S .No | Line No | $CPSI_n(j)$ | S. No | Line No | $CPSI_n(j)$ |
|---|---|---|---|---|---|
| 1 | 76 | 1 | 41 | 80 | 0.8837 |
| 2 | 36 | 0.9987 | 42 | 32 | 0.88 |
| 3 | 73 | 0.9986 | 43 | 17 | 0.8666 |
| 4 | 35 | 0.9982 | 44 | 58 | 0.863 |
| 5 | 46 | 0.9951 | 45 | 6 | 0.8616 |
| 6 | 31 | 0.9915 | 46 | 50 | 0.8593 |
| 7 | 44 | 0.991 | 47 | 68 | 0.8551 |
| 8 | 54 | 0.99 | 48 | 39 | 0.8506 |
| 9 | 29 | 0.9889 | 49 | 15 | 0.8426 |
| 10 | 19 | 0.9836 | 50 | 10 | 0.8324 |
| 11 | 74 | 0.9833 | 51 | 14 | 0.832 |
| 12 | 43 | 0.9804 | 52 | 2 | 0.8316 |
| 13 | 30 | 0.9759 | 53 | 26 | 0.8217 |
| 14 | 20 | 0.9755 | 54 | 47 | 0.8142 |
| 15 | 56 | 0.9733 | 55 | 59 | 0.8055 |
| 16 | 75 | 0.9679 | 56 | 24 | 0.8032 |
| 17 | 55 | 0.9675 | 57 | 65 | 0.7947 |
| 18 | 11 | 0.9582 | 58 | 22 | 0.794 |
| 19 | 77 | 0.9523 | 59 | 60 | 0.7883 |
| 20 | 34 | 0.9514 | 60 | 41 | 0.7746 |
| 21 | 38 | 0.951 | 61 | 21 | 0.7716 |
| 22 | 69 | 0.945 | 62 | 25 | 0.7583 |
| 23 | 70 | 0.9434 | 63 | 40 | 0.7499 |
| 24 | 64 | 0.9412 | 64 | 57 | 0.7478 |
| 25 | 42 | 0.9351 | 65 | 28 | 0.7311 |
| 26 | 16 | 0.9348 | 66 | 48 | 0.7248 |
| 27 | 67 | 0.9291 | 67 | 18 | 0.7194 |
| 28 | 66 | 0.9283 | 68 | 8 | 0.7106 |
| 29 | 27 | 0.9244 | 69 | 79 | 0.6948 |
| 30 | 78 | 0.9241 | 70 | 37 | 0.6865 |
| 31 | 7 | 0.9219 | 71 | 52 | 0.6816 |
| 32 | 9 | 0.9195 | 72 | 13 | 0.6612 |
| 33 | 12 | 0.9141 | 73 | 51 | 0.6058 |
| 34 | 71 | 0.9101 | 74 | 3 | 0.5956 |
| 35 | 5 | 0.9079 | 75 | 49 | 0.5916 |
| 36 | 4 | 0.8954 | 76 | 45 | 0.5844 |
| 37 | 62 | 0.8922 | 77 | 53 | 0.4902 |
| 38 | 63 | 0.8914 | 78 | 1 | 0.4612 |
| 39 | 23 | 0.8909 | 79 | 61 | 0.353 |
| 40 | 72 | 0.8868 | 80 | 33 | 0 |

## 5. FIREFLY ALGORITHM

The Firefly algorithm is a kind of stochastic search techniques based on the mechanism of natural behavior of fireflies. The firefly algorithm is a metaheuristic algorithm, enthused by the sporadic behavior of fireflies. The primary objective for a firefly's flash is to act as a signal system to entice other fireflies [15], [16]. This algorithm is based upon the following assumptions those are all fireflies are unisexual, so that one firefly will be a focus for all other fireflies. Charismatic is proportional to their vividness, and for any two fireflies, the less bright one will catch the fancy of the brighter one. However, the vividness can decrease as their distance increases. If there are no fireflies dazzling near a given firefly, then it will move haphazardly and the vividness should be associated with the objective function. Vividness is proportional to the value of search-space function in case of the maximization problem.
There are two important disputes in firefly algorithm, first is light intensity variation and other is vividness variation. It is assumed that vividness of the firefly is ascertained by its vividness, which in turn associated with search-space function. The vividness of the firefly is calculated as an objective value F(x) at a particular location x. Vividness is relative and it varies with distance between two fireflies. Light is also absorbed by the air and it also gets decreased with increasing distance, so vividness is allowed to show a discrepancy with the degree of absorption. The firefly algorithm function can be described as: initially consider an objective function F(x). Generate an initial population of n fireflies $X_i$, i=1, 2, 3…n. Calculate light intensity at $X_i$ which is determined by F (X). Delineate the light

absorption coefficient. Now compare the light intensities of fireflies and move the firefly which is having less light intensity towards the brighter one. Then vary the vividness with distance. Now echelon the fireflies and discover the best solution. It may create as the best. In the optimization problem where the numbers of fireflies are greater than the number of local optima, the initial locations of n fireflies should be distributed relatively uniformly throughout the entire search space. During the execution, the fireflies converge into all of these local optima, the global optima is determined. Firefly algorithm will approach the global optima when n tends to infinite and number of iterations is greater than 1 but in reality it has abrupt convergence. The basic steps of the FA can be summarized by the pseudo code [17].

The step by step implementation of Firefly algorithm can be described as follows:

*Step I. Initialize the load flow data, and Firefly parameters such as the size of the population (N) , the maximum number of generations (N_gen), Randomness, Absorption coefficient and the number of variables to be optimized (D).*

*Step II. Generate the initial population of N individuals randomly in the feasible area. Consider the optimized variables. (i.e. the real and reactive power generation of the generator buses, the parameter setting of the TCSC). Therefore, all the solutions are practicable solutions and the object is to find the best possible one.*

*Step III. Evaluate the fitness for each individual in the population according to the objective function.*

*Step IV. Generate a new resident.*

*Step V: Stop the process and print the best individual if the stopping criterion is satisfied, else go back to step IV.*

## 6. RESULTS AND DISSCUSSION

In order to find the use of the Firefly Algorithm for Optimal Power Flow with the TCSC, the IEEE57 bus system is taken. An OPF program using Firefly algorithm is implemented in MATLAB software without and with the TCSC. The results are presented and analysed. The input parameters of Firefly Algorithm for the test system are given in the Table 2. The generator characteristics of the IEEE 57 bus are given in Table 3.

**Table 2.** Input parameters of Firefly Algorithm

| S. No | Parameters | Quantity |
|---|---|---|
| 1 | Number of fireflies | 20 |
| 2 | Max Generation | 50 |
| 3 | Alpha | 0.5 |
| 4 | Beta | 0.5 |
| 5 | Gama | 1 |

**Table 3.** Generator Characteristics of IEEE 57 Bus System

| Generator bus number | a ($/MW$^2$/hr) | b ($/MW/hr) | c ($/hr) | $P_G^{min}$ (MW) | $P_G^{max}$ (MW) |
|---|---|---|---|---|---|
| 1 | 0.0775 | 20 | 0 | 0 | 575 |
| 2 | 0.01 | 40 | 0 | 0 | 100 |
| 3 | 0.25 | 20 | 0 | 0 | 140 |
| 6 | 0.1 | 40 | 0 | 0 | 100 |
| 8 | 0.02222 | 20 | 0 | 0 | 550 |
| 9 | 0.01 | 40 | 0 | 0 | 200 |
| 12 | 0.32258 | 20 | 0 | 0 | 410 |

In IEEE 57 bus system, bus 1 is considered as slack bus and buses 2,3,6,8,9,12 are considered as generator buses. It consists of 50 load buses and 80 transmission lines. Considering all the parameters of the system, generation reallocation is carried out with a multi objective function which is formed by considering the cost of the real power generation, active power losses, voltage deviation and branch loading. Results are presented in Table 4 to 6.

As metaheuristic algorithms are based on probabilistic approach, the solutions obtained are not unique. The Firefly algorithm based Optimal Power Flows is run 50 times and its best, worst and average values are determined. The best value is considered for Optimal Power Flow solution.

**Table 4.** Objective function parameters of multi objective optimization using FA-OPF considering without TCSC in IEEE 57 bus system

| | FA-OPF without TCSC | | |
|---|---|---|---|
| Variables | (Best) | (Average) | (Worst) |
| PG1(MW) | 276.2743 | 276.3723 | 277.4703 |
| PG2(MW) | 46.3705 | 46.624 | 46.4775 |
| PG3(MW) | 90.1467 | 90.28095 | 91.4152 |
| PG6(MW) | 51.1067 | 51.25265 | 51.7986 |
| PG8(MW) | 549.4493 | 549.6961 | 549.9428 |
| PG9(MW) | 152.2256 | 152.6625 | 153.0993 |

| | | | |
|---|---|---|---|
| PG12(MW) | 76.2740 | 76.97365 | 77.6733 |
| Total real power generation (MW) | 1241.847 | 1243.862 | 1247.877 |
| Total reactive power generation (MVAR) | 341.5264 | 355.8214 | 382.1164 |
| Total real power generation cost ($/hr) | 46977.18 | 47002.45 | 47027.71 |
| Active power Loss (MW) | 46.0472 | 48.0621 | 52.0772 |
| Voltage deviation (p.u) | 5.7421 | 5.89075 | 6.0394 |
| Branch loading (p.u) | 13.3127 | 13.50345 | 13.8942 |
| FVSI value for all lines (p.u) | 7.6171 | 7.7984 | 8.1797 |
| Reactance of TCSC | ---- | ------ | ---- |
| Objective function value | 11760.57 | 11767.01 | 11773.44 |

**Table 5.** Objective function parameters of multi objective optimization using FA-OPF considering with TCSC in IEEE 57 bus system

| | FA- OPF with TCSC connected in Line number 76 | | |
|---|---|---|---|
| Variables | (Best) | (Average) | (Worst) |
| PG1(MW) | 258.3014 | 259.2575 | 260.2136 |
| PG2(MW) | 73.8020 | 74.09415 | 74.3863 |
| PG3(MW) | 74.7152 | 74.79305 | 74.8709 |
| PG6(MW) | 65.3063 | 65.47055 | 65.6348 |
| PG8(MW) | 549.9490 | 549.7355 | 549.5220 |
| PG9(MW) | 141.3715 | 141.5272 | 141.6829 |
| PG12(MW) | 77.1977 | 77.3757 | 77.5537 |
| Total real power generation (MW) | 1240.643 | 1242.254 | 1243.864 |
| Total reactive power generation (MVAR) | 309.4265 | 318.978 | 368.5294 |
| Total real power generation cost ($/hr) | 46412.35 | 46483 | 46553.63 |
| Active power Loss (MW) | 44.8432 | 46.4538 | 48.0644 |
| Voltage deviation (p.u) | 4.8530 | 5.095 | 5.7370 |
| Branch loading (p.u) | 12.7971 | 13.0313 | 13.2655 |
| FVSI value for all lines (p.u) | 7.3326 | 7.5435 | 8.1544 |
| Reactance of TCSC (p.u) | 0.3111 | 0.3238 | 0.3405 |
| Objective function value | 11618.96 | 11637.19 | 11655.42 |

The results from Table 4, 5, 6 show that , for minimization of the multi objective function by using Firefly algorithm with TCSC, the generation cost of the best solution is 46412.3565$/hr with 44.8432 MW line loss, 4.8530 voltage deviation and 12.7971 branch loading. The results in Table VI indicate the values of the different parameters of the multi objective function using Firefly algorithm and genetic algorithm considering without & with TCSC. From this table it is observed that Firefly algorithm gives better results compared to genetic algorithm.

**Table 6.** Comparison of objective function parameters using GA and FA-OPF considering without and with TCSC in IEEE 57 bus system

| Variables | GA-OPF without TCSC | FA-OPF without TCSC | GA OPF with TCSC at line no 76 | FA- OPF with TCSC at line no 76 |
|---|---|---|---|---|
| PG1(MW) | 242.8286 | 276.2743 | 241.8295 | 258.3014 |
| PG2(MW) | 100.0000 | 46.3705 | 100.0000 | 73.8020 |
| PG3(MW) | 71.9212 | 90.1467 | 69.8740 | 74.7152 |
| PG6(MW) | 100.0000 | 51.1067 | 100.0000 | 65.3063 |
| PG8(MW) | 550.0000 | 549.4493 | 550.0000 | 549.9490 |
| PG9(MW) | 110.6312 | 152.2256 | 110.6312 | 141.3715 |
| PG12(MW) | 69.8740 | 76.2740 | 71.9212 | 77.1977 |
| Total real power generation (MW) | 1245.255 | 1241.847 | 1244.255 | 1240.643 |
| Total reactive power generation (MVAR) | 354.4808 | 341.5264 | 321.1757 | 309.4265 |
| Total real power generation cost ($/hr) | 47701.16 | 46977.18 | 47689.09 | 46412.35 |
| Active power Loss (MW) | 49.4550 | 46.0472 | 49.2455 | 44.8432 |
| Voltage deviation (p.u) | 5.9295 | 5.7421 | 4.9056 | 4.8530 |
| Branch loading (p.u) | 13.8480 | 13.3127 | 14.1600 | 12.7971 |
| FVSI value for all lines (p.u) | 7.9431 | 7.6171 | 7.5205 | 7.3326 |
| Reactance of TCSC (p.u) | ---- | ---- | 0.4201 | 0.3111 |
| Objective function value | 11942.59 | 11760.57 | 11939.35 | 11618.96 |

From Figure 3 it is observed that the active power losses of the system are reduced by an appreciable amount with the placement of TCSC in Firefly algorithm based Optimal Power Flow.

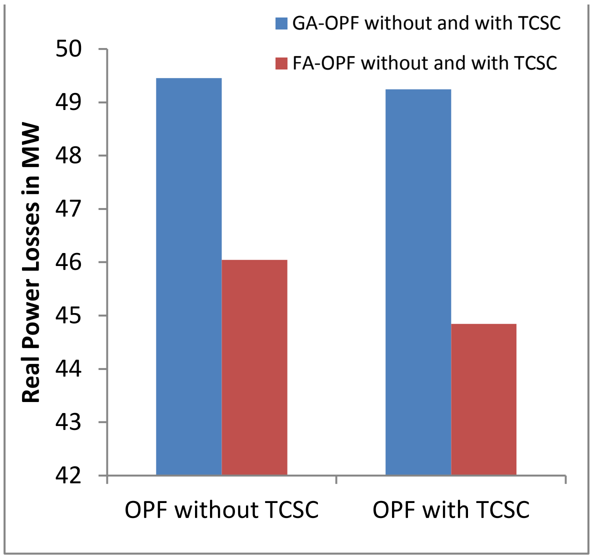


**Fig. 3**. Comparisons of Real Power Losses

Table 7 indicates the reactance of TCSC for different specified real power flows through the line. From this Table it has been observed that by increasing power flow through the line, reactance of TCSC value has been decreased.

**Table 7.** Reactance of TCSC for Different Methods with Specified Power Flow in TCSC (TCSC placed in Line number 76)

| S.No | Real power flow through TCSC installed line | $X_{TCSC}$ (GA-OPF with TCSC) | $X_{TCSC}$ (FA-OPF with TCSC) |
|---|---|---|---|
| 1 | P=1MW | 4.6656 | 4.5355 |
| 2 | P=1.5MW | 2.5481 | 2.2900 |
| 3 | P=2MW | 1.4457 | 1.2916 |
| 4 | P=2.5MW | 0.7341 | 0.5922 |
| 5 | P=3MW | 0.4201 | 0.3111 |
| 6 | P=3.1MW | 0.1383 | 0.0759 |

**Table 8.** Best, Worst and Average of the Objective Function value for IEEE57-Bus System Using Firefly Algorithm

| function | γ=1 β=0.2 | γ=1 β=0.2 | γ=1 β=0.5 | γ=1 β=0.5 |
|---|---|---|---|---|
| Average | 11776.5986 | 11783.926 | 11776.8334 | 11764.9974 |
| Worst | 11828.7426 | 11787.3778 | 11776.8334 | 11772.8469 |
| Best | 11768.19 | 11782.542 | 11766.5818 | **11760.5724** |

*α, β = randomness coefficients, γ = absorption coefficient

Table 8 represents the objective function values with varying Firefly algorithm parameters and it is observed that taking randomness coefficients equal to 0.5 and absorption coefficient equal to one in Firefly algorithm gave better results compared to other values, so in this analysis Firefly algorithm parameters are considered as above values.

Figure 4 and Figure 5 show the convergence of the objective function using Firefly algorithm and Genetic algorithm considering without and with TCSC respectively. From these figures it is observed that Genetic Algorithm takes more number of generations to converge when compared to Firefly algorithm. Firefly Algorithm gives better result and converges quickly.

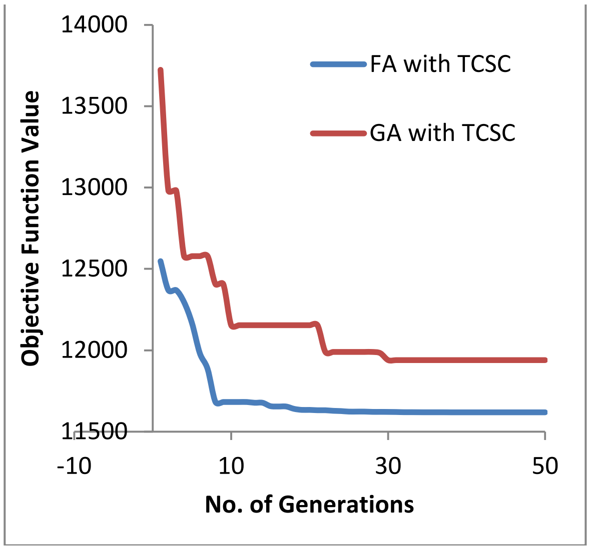


**Fig. 4.** Convergence of the Objective Function using FA and GA with TCSC

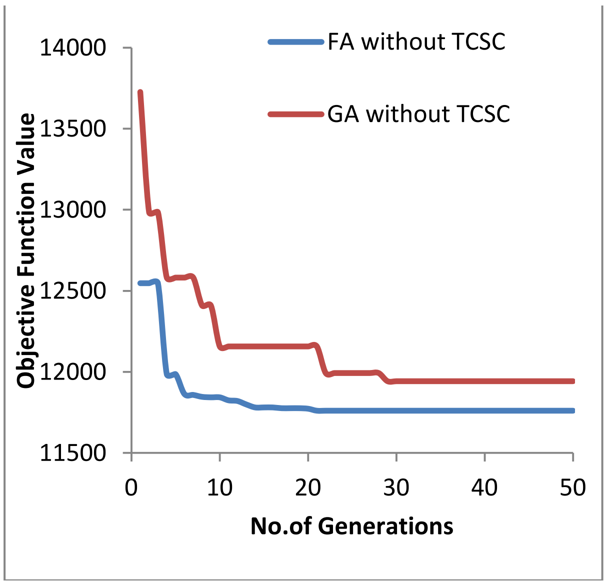


**Fig. 5.** Convergence of the objective function using FA and GA without TCSC

Figure 6 represents the comparison of voltage profiles with and without TCSC using Firefly Algorithm. It is observed that by installing TCSC optimally in power systems, it improves the voltage profile of the buses. Figure 7 represents the Fast Voltage Stability Index for lines with and without TCSC using Firefly Algorithm. It is observed that by incorporating the TCSC in the system, voltage stability has been improved.

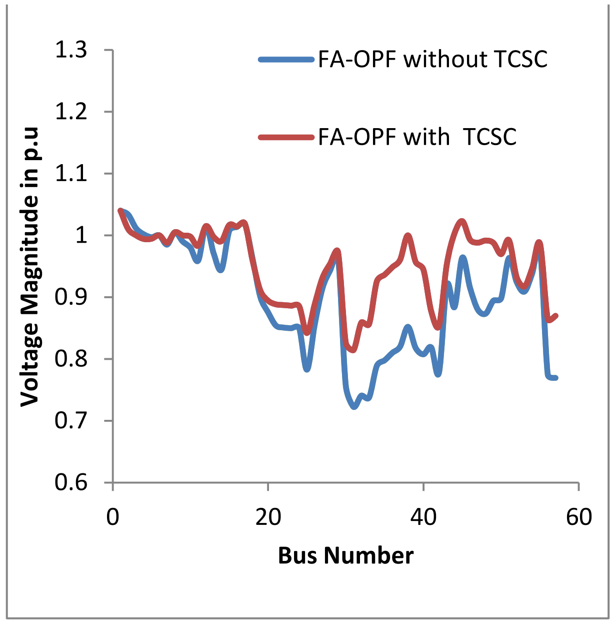


**Fig. 6.** Comparison of the Voltage Magnitudes with and without TCSC

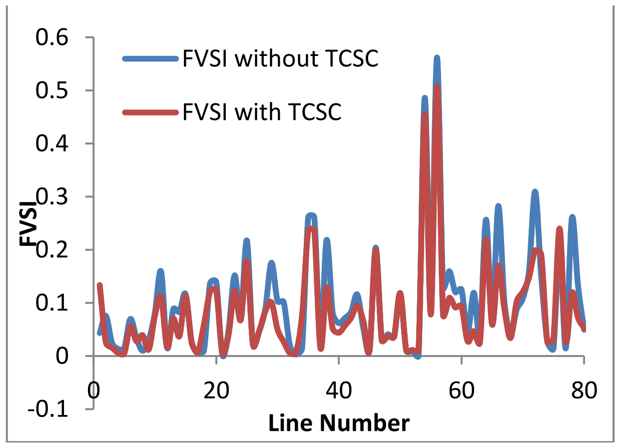


**Fig. 7.** Comparison of the FVSI with and without TCSC using Firefly Algorithm

## 7. CONCLUSION

In this paper, the system performance is valued with the placement of series compensating device TCSC using Genetic and Firefly algorithms. The placement of the TCSC is done through Complex Power Flow Sensitivity index, while sizing and generation reallocation is obtained through Firefly and Genetic algorithms. Optimal Power Flow solutions for the system are obtained by considering a multi objective function. The results obtained for the IEEE 57 bus systems using the proposed methods without and with TCSC disclose a noticeable reduction in real power losses and increase in power transfer capability in transmission lines by incorporating TCSC in the system. In view of the technique employed the Firefly algorithm gave a better performance than Genetic algorithm.

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