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# Complex Power Flow Sensitivity Index based Optimal Location and Tuning of Thyristor Controlled Series Capacitor using BAT Algorithm to enhance Line based Voltage Stability

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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 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 Complex Power Flow Sensitivity Index (CPSI) calculated for placing the TCSC at an appropriate location. Once the location to install the TCSC is determined, the optimal tuning of the TCSC is determined through BAT Algorithm. The BAT Algorithm is implemented on multi-criterion objective function to minimize total real power loss, total voltage magnitude deviations, the fuel cost of total real power generation and the branch loading to obtain the Optimal Power Flow. Simulations have been carried out in MATLAB software for the IEEE 57-bus system. The results have been taken for BAT Algorithm based Optimal Power Flow without and with TCSC. The results obtained with BAT Algorithm were compared with Genetic Algorithm (GA).**

***Keywords- BAT Algorithm, Optimal placement, Sensitivity index, TCSC .***

## I. INTRODUCTION

Power systems are becoming increasingly more complex due to the interconnection of regional system and deregulation of the overall electricity market (Kundur 1993; Stagg & El- Abid 1968). The existing power network capacities can be increased by installing the Flexible AC Transmission System (FACTS) controllers. The parameters of the transmission line, like line reactance, voltage magnitude, and phase angle can to be controlled using the FACTS controllers in a fast and effective way. The credits of the FACTS controllers include improvement of the stability of power system networks, such as voltage stability, line stability, small signal stability, transient stability, enhance power transfer capability and thus enhance system reliability. However, controlling power flows is the main function of the FACTS controllers (Gyugyi & Hingorani 2000; Acha *et al* 1999).

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 [5, 6]. It regulates the power flow through the transmission line (Lei & Retzmann 2000). 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 (Christa *et al* 2013).The optimal placement of Thyristor Controlled Series Compensators in transmission systems is formulated as a multi-objective optimization problem to minimize the losses ( Basu 2008).

This paper presents a Sensitivity analysis based Complex Power Flow Sensitivity Index (CPSI) proposed for placing the TCSC at appropriate location. A new Metaheuristic optimization technique called the BAT algorithm is introduced to find the optimal size of the TCSC device to improve stability. Its performance is compared with the Genetic Algorithm (GA) technique. The real and reactive power generation values and voltage limits for 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.

## II. PROBLEM FORMULATION

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

### A. *Objective function*

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

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

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:

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

#### 1) *Fuel cost:*

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

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

Where ng = no. of generator buses

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

#### 2) *Active Power Loss:*

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

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

Where ntl=no. Of transmission lines

$S_{ij}$ is the total complex power flow of line i – j

#### 3) *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:

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

$V_k$ is the voltage magnitude at bus k

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

#### 4) *Branch loading:*

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

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

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

#### 5) *Equality constraints:*

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

Where i=1,2,3,.......,$N_{bus}$ and $N_{bus}$ = no. of. Buses

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

Where i=1,2,3,.......,$N_{bus}$ and $N_{bus}$ = no. of. buses

$P_L$ is total active power losses

$Q_L$ is total reactive power losses

#### 6) *Inequality constraints:*

##### a) *Generator bus Voltage limits:*

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

Where i=1,2,3,.......,$N_{bus}$ and $N_{bus}$ = no.of. buses

##### b) *Real power generation limit:*

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

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

##### c) *Reactive Powergeneration limits:*

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

### B. *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 proposed 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.

#### 1) *FVSI (Fast Voltage Stability Index)*

FVSI can be expressed as

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

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)

Any line in the system that exhibits FVSI close to unity indicate that the line is may lead to system violation. Therefore, FVSI has to be maintained less than unity in order to maintain a stable system.

## III. 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 (Gerbex and Germond 2001; Acha *et al* 2000; Ambriz- Perez *et al* 2006 ). Thyristor inhibition in the TCSC module enables it to have a smoother control over its reactance in response to system parameter variations.

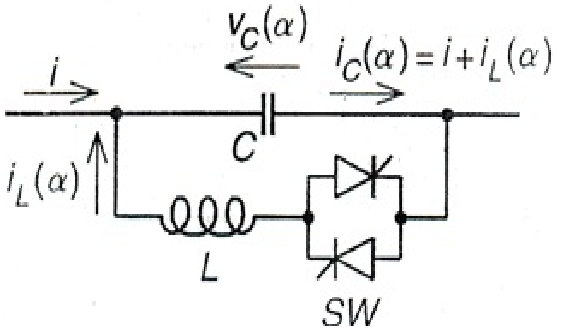

Figure1. Basic TCSC model

$X_C$ = fixed capacitive impedance
$X_L$ (α) = variable inductive impedance

$$X_{TCSC}(\propto) = \frac{X_C\, X_L(\propto)}{X_L(\propto) - X_C} \qquad (13)$$

Where

$$X_L(\propto) = \frac{X_L(\pi)}{\pi - 2\propto - (\sin 2\propto)}$$

$$X_{Lmin} \le X_L(\propto) \le X_{Lmax} \qquad (14)$$

Where $X_L = \omega L$ and α = delay angle

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 to constraint the power flow across the branch is specified. The amount of reactance is determined efficiently using BAT 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 (Abdel & Padhy 2005).

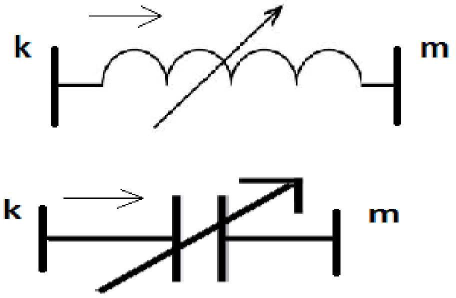

Figure 2. Thyristor-controlled series capacitor equivalent circuit: Inductive and capacitive operative regions

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

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \qquad (15)$$

For capacitive operation, we have

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

$$B_{km} = B_{mk} = \frac{1}{X_{TCSC}} \qquad (16)$$

For inductive operation the signs are reversed

The active and reactive power equations at bus k are:

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

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

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

$$\Delta X_{TCSC} = X^{i}_{TCSC} - X^{(i-1)}_{TCSC} \qquad (19)$$

The state variable XTCSC of the series controller is updated at the end of each iterative step according to

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

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

A method based on the sensitivity of 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 capacitive reactance $X_{TCSC}$, resulting in a decrease of the total line reactance. The index is computed using Newton Raphson power flow. $CPSI_j$ at a line j is given as:

$$CPSI_j = \sum_{n=1}^{ntl} \frac{\Delta Sn}{\Delta Xj} \qquad (21)$$

Where n=1, 2, 3,......., ntl and ntl = no.of transmission lines.

$\Delta Sn$ is change in complex power flow in line n

$\Delta Xj$ is 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:

$$CPSI_{nj} = \frac{CPSI_j - CPSI_{min}}{CPSI_{max} - CPSI_{min}} \qquad (22)$$

where $CPSI_{nj}$ 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 4.1 it is observed that highest positive value of $CPSI_n(j)$ is 1 for line no 76 and TCSC is placed in line number 76. Complex power flow sensitivity Indexes for all lines in the IEEE 57 bus system.

TABLE I.

COMPLEX POWER FLOW SENSITIVITY INDEXES 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 |

## V. OPTIMAL SIZING OF TCSC USING THE BAT ALGORITHM

The BAT algorithm has been used to find the optimum sizing of TCSC. BAT Algorithm is a nature inspired metaheuristic algorithm which is developed by Xin-She Yang in 2010. Metaheuristic algorithms use certain trade-off of randomization and local search. Randomization supplies a good way to move away from local search to the search on the global scale (Yang 2008). This algorithm is based on the echolocation behaviour of micro bats. Micro bats use a type of sonar to detect food and prey, avoid obstacles and locate their roosting chink in the dark. These bats emit a very loud sound pulse and listen for the echo that bounces back from surrounding objects. BAT algorithm is developed by considering some of the characteristics of micro bats following the rules. (Yang 2011)

### *A. Population*

The initial population i.e., number of virtual bats for BAT (n) is generated randomly. The number of bats may be anywhere between 0 and 20. After finding the initial fitness of the population for the given function, the values are modified based on their movement, intensity and pulse rate.

### *B. Movement of Virtual Bats*

The rules for modifying the positions xii and velocities vii of the virtual bats are given as (23)

$$f_{ii} = f_{min} + (f_{\max} - f_{\min})\beta \qquad (23)$$

$$v_{ii}^{t} = v_{ii}^{t-1} + (x_{ii}^{t} - x_0)\, f_{ii}$$

$$x_{ii}^{t} = x_{ii}^{t-1} + v_{ii}^{t}$$

Where, β ∈ [0, 1] is a random vector drawn from an identical distribution. Here xo is the current global best location which is located after comparing all the solutions with all the n bats. For the local search part, once a solution is selected in current best solutions, a new solution for each bat is create locally using random walk given by equation (24)

$$x_{new} = x_{old} + \epsilon A^{t} \qquad (24)$$

where $\varepsilon \in [-1, 1]$ is a random number, while At =<Ait > is the average loudness of all the bats at this time step. Based on these approximations and admiration, the basic steps of the BAT Algorithm can be iterate as the pseudo code (Yang 2010).

### *C. Loudness and Pulse Emission*

The loudness Aii and the rate of pulse emission rii are updated accordingly as the iterations proceed. The loudness decreases and rate of pulse emission increases as the bat closes on its food i.e., the equations for convergence can be taken as below.

$$A_{ii}^{t+1} = \alpha A_{ii}^{t}$$

$$R_{ii}^{t+1} = r_{ii}^{0}[1 - \exp(-\gamma t)]$$

, Where α and γ are constants.

For any 0< α <1 and γ >0, we have

$$A_{ii}^{t} \to 0, r_{ii}^{t} \to r_{ii}^{0} \text{ as } t \to \infty$$

The initial loudness A0 can typically be (1, 2), while the initial emission rate $ri$i0 can be (0, 1).

## VI. RESULTS AND DISCUSSION

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

TABLE II

INPUT PARAMETERS OF BAT ALGORITHM

| S.No | Parameters | Quantity |
|---|---|---|
| 1 | Population size | 20 |
| 2 | Number of generations | 50 |
| 3 | Loudness | 0.5 |
| 4 | Pulse rate | 0.5 |

TABLE III

GENERATOR CHARACTERISTICS OF IEEE 57 BUS SYSTEM

| Generator bus no | 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 IV to VI.

As metaheuristic algorithms are based on probabilistic approach, the solutions obtained are not unique. The BAT 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 IV

COMPARISON OF OBJECTIVE FUNCTION PARAMETERS OF MULTI OBJECTIVE OPTIMIZATION USING BAT-OPF CONSIDERING WITHOUT IN IEEE 57 BUS SYSTEM

| | BAT-OPF without TCSC | | |
|---|---|---|---|
| Variables | (Best) | (Average) | (Worst) |
| PG1(MW) | 167.4362 | 175.9858 | 184.5353 |
| PG2(MW) | 85.3003 | 90.71105 | 96.1218 |
| PG3(MW) | 140.0000 | 140 | 140.0000 |
| PG6(MW) | 41.6669 | 48.78105 | 55.8952 |
| PG8(MW) | 550.0000 | 550 | 550.0000 |
| PG9(MW) | 200.0000 | 196.0988 | 192.1975 |
| PG12(MW) | 60.2578 | 47.1392 | 34.0206 |
| Total real power generation | 1244.6612 | 1248.716 | 1252.7704 |
| Total reactive power generation | 350.7705 | 375.684 | 400.5975 |
| Total real power generation cost | 47144.4847 | 47296.22 | 47447.9501 |
| Active power Loss | 48.8612 | 52.9158 | 56.9704 |
| Voltage deviation | 5.7725 | 6.45445 | 7.1364 |
| Branch loading | 13.8017 | 14.25145 | 14.7012 |
| FVSI | 7.8545 | 8.47325 | 9.0920 |
| Reactance of TCSC | --- | ---- | ---- |
| Objective function value | 11803.2300 | 11842.46 | 11881.6895 |

TABLE V

COMPARISON OF OBJECTIVE FUNCTION PARAMETERS OF MULTI OBJECTIVE OPTIMIZATION USING BAT-OPF CONSIDERING WITH TCSC IN IEEE 57 BUS SYSTEM

| | BAT OPF with TCSC connected in Line no 76 | | |
|---|---|---|---|
| Variables | (Best) | (Average) | (Worst) |
| PG1(MW) | 191.4760 | 187.4594 | 183.4427 |
| PG2(MW) | 45.5955 | 67.12505 | 88.6546 |
| PG3(MW) | 58.8534 | 55.5613 | 52.2692 |
| PG6(MW) | 98.0000 | 84.95275 | 71.9055 |
| PG8(MW) | 550.0000 | 550 | 550.0000 |
| PG9(MW) | 200.0000 | 200 | 200.0000 |
| PG12(MW) | 98.5849 | 98.4601 | 98.3353 |
| Total real power generation | 1242.5099 | 1243.559 | 1244.6073 |
| Total reactive power generation | 338.4303 | 351.7879 | 365.1454 |
| Total real power generation cost | 46789.0644 | 46809.94 | 46830.8147 |
| Active power Loss | 46.7099 | 47.7586 | 48.8073 |
| Voltage deviation | 4.9258 | 5.36205 | 5.7983 |
| Branch loading | 13.8640 | 14.0726 | 14.2812 |
| FVSI | 7.7512 | 8.14505 | 8.5389 |
| Reactance of TCSC | 0.3278 | 0.3348 | 0.3418 |
| Objective function value | 11713.6410 | 11719.28 | 11724.9254 |

The results from Table VI, V, VI show that , for minimization of the multi objective function, the generation cost of the best solution is 46789.0644 \$/hr with 46.7099 MW line loss, 4.9258 voltage deviation and 13.8640 branch loading. The results in Table VI indicate the values of the different parameters of the different objective function using BAT considering with TCSC. From this table it can be observed that all the objective function parameters are optimized simultaneously.

TABLE VI

COMPARISON OF OBJECTIVE FUNCTION PARAMETERS USING GA, BAT, FA-OPF CONSIDERING WITHOUT AND WITH TCSC IN IEEE 57 BUS SYSTEM

| Variables | GA-OPF without TCSC | BAT-OPF without TCSC | GA OPF with TCSC at line no 76 | BAT OPF with TCSC at line no 76 |
|---|---|---|---|---|
| PG1(MW) | 242.828 | 167.43 | 241.8295 | 191.4760 |
| PG2(MW) | 100.000 | 85.300 | 100.0000 | 45.5955 |
| PG3(MW) | 71.9212 | 140.00 | 69.8740 | 58.8534 |
| PG6(MW) | 100.000 | 41.666 | 100.0000 | 98.0000 |
| PG8(MW) | 550.000 | 550.00 | 550.0000 | 550.0000 |
| PG9(MW) | 110.631 | 200.00 | 110.6312 | 200.0000 |
| PG12(MW) | 69.8740 | 60.257 | 71.9212 | 98.5849 |
| Total real power generation | 1245.25 | 1244.6 | 1244.255 | 1242.5099 |
| Total reactive power generation | 354.480 | 350.77 | 321.1757 | 338.4303 |
| Total real power generation cost | 47701.1 | 47144.4 | 47689.09 | 46789.0 |
| Active power Loss | 49.4550 | 48.861 | 49.2455 | 46.7099 |
| Voltage deviation | 5.9295 | 5.7725 | 4.9056 | 4.9258 |
| Branch loading | 13.8480 | 13.801 | 14.1600 | 13.8640 |
| FVSI | 7.9431 | 7.8545 | 7.5205 | 7.7512 |
| Reactance of TCSC | ---- | --- | 0.4201 | 0.3278 |
| Objective function value | 11942.5 | 11803.2 | 11939.35 | 11713.6 |

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 BAT algorithm.

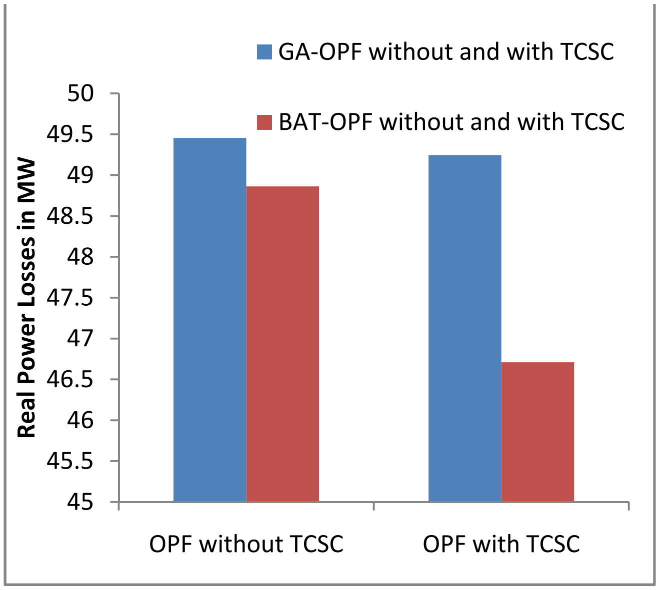

Figure3. comparisons of Real Power Losses

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

TABLE VII

REACTANCE OF TCSC FOR DIFFERENT METHODS WITH SPECIFIED POWER FLOW IN TCSC (TCSC PLACED IN LINE NO 76)

| S.No | Real power flow through TCSC installed line | GA-OPF with TCSC $X_{tcsc}$ | BAT-OPF with TCSC $X_{tcsc}$ |
|---|---|---|---|
| 1 | P=1MW | 4.6656 | 4.6474 |
| 2 | P=1.5MW | 2.5481 | 2.3672 |
| 3 | P=2MW | 1.4457 | 1.2928 |
| 4 | P=2.5MW | 0.7341 | 0.6366 |
| 5 | P=3MW | 0.4201 | 0.3278 |
| 6 | P=3.1MW | 0.1383 | 0.0850 |

TABLE VIII

BEST, WORST AND AVERAGE OF OBJECTIVE FUNCTION FOR IEEE57-BUS SYSTEM USING BAT ALGORITHM

| Objective function value | L=0.2<br>PR=0.2 | L=0.5<br>PR=0.2 | L=0.2<br>PR=0.5 | L=0.5<br>PR=0.5 |
|---|---|---|---|---|
| Average | 11845.98 | 11854.98 | 11823.665 | 11814.434 |
| Worst | 11888.79 | 11870.84 | 11841.804 | 11825.123 |
| Best | 11836.98 | 11830.47 | 11811.232 | 11803.230 |

L= Loudness PR=Pulse Rate

Table VIII represents the objective function values with varying BAT algorithm parameters and it is observed that taking Loudness and Pulse rate equal to 0.5 in BAT algorithm gave better results compared to other values, so in this analysis BAT parameters are considered as 0.5.

Figure .4, Figure .5 shows the convergence of the objective function using BAT 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 BAT. From these figures it is observed that BAT Algorithm gives better result and takes less number of generations to converge. Same thing is holds good for without TCSC.

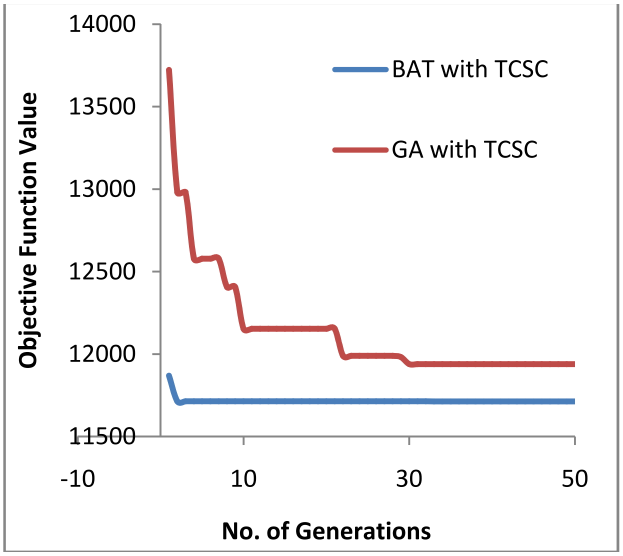

Figure 4. Convergence of the Objective Function with BAT and GA

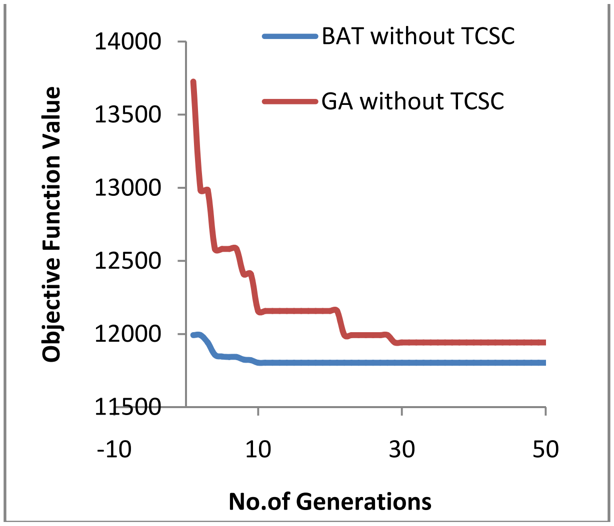

Figure 5. Convergence of the objective function with BAT and GA without TCSC

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

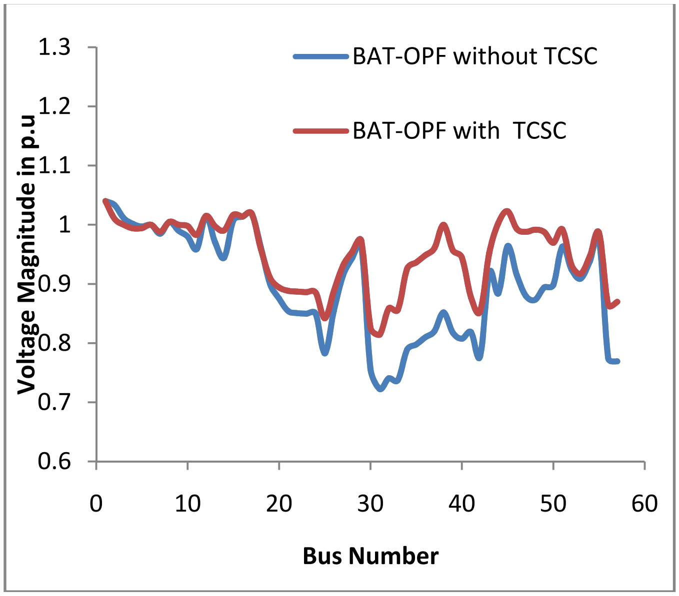

Figure 6. Comparison of the Voltage Magnitudes with and without TCSC

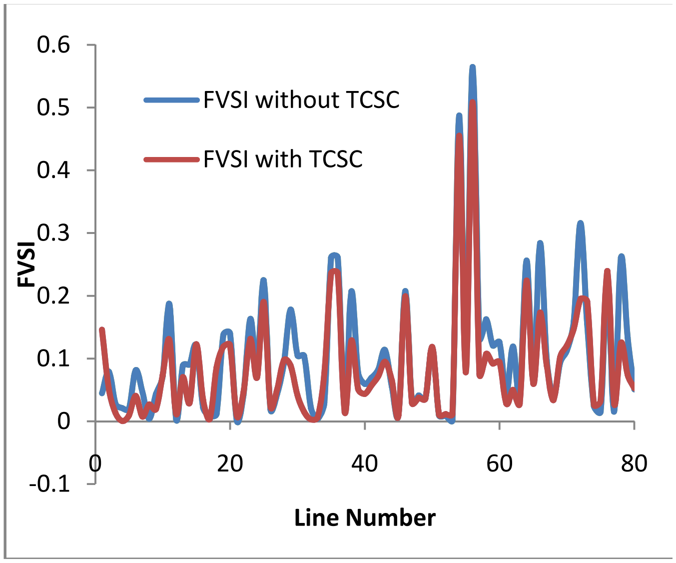

Figure 7. Comparison of FVSI with and without TCSC using BAT Algorithm

## VII. CONCLUSION

In this paper, Sensitivity Analysis based Complex Power Flow Sensitivity Index (CPSI) has been implemented for optimal location of the TCSC. After placing the TCSC in the best location, a new swarm based BAT Algorithm has been presented to solve the optimal sizing of TCSC. The effectiveness of BAT Algorithm was presented. The results show that incorporating the TCSC in the IEEE 57 bus system can reduce the total active power losses, improve the voltage profile of the system and enhance the line based voltage stability. For finding the best size of a TCSC, BAT Algorithm based optimization technique, with the objective of reducing total generation cost, voltage deviation, active power losses and branch loading was implemented. The comparative study of the BAT Algorithm based Optimal Power Flow with GA based Optimal Power Flow in solving the optimal tunning problem, indicates the effectiveness of the proposed approach. The obtained results show that the TCSC is the most effective series compensation device that can significantly increase the line based voltage stability of the power system.

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