Optimal Location of Thyristor Controlled Series Capacitor for reduction of Transmission Line losses using BAT Search Algorithm

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Abstract: - This paper presents a new metaheuristic algorithm called BAT search Algorithm (BAT). The BAT search algorithm is used to solve Optimal Power Flow (OPF) problem with the Thyristor Controlled Series Capacitor (TCSC). The TCSC is used to reduce the transmission line losses and improve the voltage profile of the power system. The effectiveness of the BAT Algorithm has been tested for various bus systems like 5 bus test system, the IEEE 14 bus system and the modified IEEE 30 bus system. The obtained results were compared with Genetic Algorithm (GA) and Differential Evolution (DE) with and without TCSC. Results clearly indicate the effectiveness of the BAT Algorithm over the Genetic algorithm and the Differential Evolution algorithms in solving OPF problem with the TCSC.

Key-Words: - BAT Algorithm, Differential Evolution, FACTS device, Genetic Algorithm, Optimal Power Flow, TCSC.

Nomenclature

$V_i \angle \theta$	: Complex voltage at bus i;
θ_{ij}	: Difference between θ_i and θ_j
F	: Objective function
V_i	: Bus voltage at ith bus
V_i^{min}	: Minimum voltage at bus i
V_i^{max}	: Maximum voltage at bus i
P_{Gi}^{min}	: Minimum real power generation of bus i
P_{Gi}^{max}	: Maximum real power generation of bus i
Q_{Gi}^{min}	: Minimum reactive power generation of bus i
Q_{Gi}^{max}	: Maximum reactive power generation of bus i
S_{ij}	: Apparent power flow from bus i to j
P_{ij}	: Active power flow from bus i to j
Q_{ij}	: Reactive power flow from bus i to j
Y_{ij}	: Admittance of the element between bus i and j
Z	: Line impedance
X	: Line reactance
X_{TCSC}	: Reactance of the TCSC
P_L	: Active power losses
P_{Di}	: The active power demand at bus i
P_{Gi}	: Real power generation of bus i
ng	: Number of generator buses
N	: Number of buses

1 Introduction

Modern electric power utilities are facing many challenges due to increasing complexity in their operation and structure. In the recent history, one of the problems that got wide attention is the power system instabilities [1]. Due to lack of new generation and transmission facilities and over exploitation of the existing facilities, along with increase in load demand, unavoidable in modern power systems. Conventional power systems are controlled mechanically. Power system instabilities are frequently control through mechanical devices as circuit breakers is not as reliable as compared to static devices as mechanical devices are subjected to wear out quickly. The consequences of this lack of fast control resulted in poor utilization of the transmission resources, improper var flows and maximum losses. Therefore Power flow should be electronically controlled and it should be flexible. The power electronic based Flexible AC Transmission System (FACTS) have been introduced in 1980's and used as economical and efficient means to control the power transfer in an interconnected AC transmission system [2, 3]. It has become essential to better utilize the existing power networks to increase capacities by installing FACTS controllers. Power flow through an AC line is a function of phase angles, bus voltages and line impedance and there is little or no control over any of these variables. With FACTS devices one can control the phase angle, the voltage magnitude at chosen buses and/or line impedances. The advantages derived from FACTS 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 FACTS [4, 5].

Out of the several preventive and corrective measures suggested in literature to protect power system networks against voltage collapse, the placement of the 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. Power flow has been optimized by placement of the FACTS controllers [6, 7]. There are several papers in literature, which deal with the optimal placement of FACTS controllers with heuristic methods. References [8-10] deal with the location of FACTS devices using GA, DE. And [11] discusses the location of the TCSC under normal and contingency conditions. In recent years, several biologically inspired algorithms have been developed, to find solutions of complex optimization problems. Optimal location of different types of FACTS devices in the power system has been attempted using different techniques such as PSO, DE presented in [12]. The best location of Unified Power Flow Controller for enhancement of static and transient voltage stability has been presented in [13]. TCSC control design explained using PSO and Bacterial Foraging in [14]. Enhancement of Voltage Stability in radial system using Static VAR Compensator explained in [15]. Optimal allocation of FACTS devices has been explained in [16, 17]. The Thyristor Controlled Series Capacitor (TCSC) is one of the most effective Flexible AC Transmission System (FACTS) devices for series compensation. The power flow can be increased by decreasing the line impedance with a capacitive reactance it leads to reduction in transmission line losses [18, 19].

In this paper, the ideal location for placement of FACTS device has been formulated as a problem, and is solved using a new metaheuristic algorithm called the BAT search Algorithm. The BAT search Algorithm is used for finding out the optimal locations of Thyristor Controlled Series Compensator (TCSC) devices, to achieve minimum transmission line losses in the system. The BAT algorithm results are compared with the results of the Genetic Algorithm (GA) and the Differential Evolution (DE) techniques. The voltage limits for the buses and the lines thermal limits are taken as constraints during the optimization. Computer simulations using MATLAB were done for a 5 bus system, the IEEE14 bus system and the modified IEEE 30 bus system.

2 TCSC Model

2.1 Representation of the TCSC in Power Flow Analysis

The basic Thyristor-controlled series capacitor scheme proposed in 1986 by Vithaythil with others is based on a method of “rapid adjustment of network impedance” [20-22]. Apart from enhancing system stability, TCSC also increases the line power transfer capability. The basic module of the TCSC is shown in Fig. 1. It consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors[23,24]. Thyristor inhibition in the TCSC module enables it to have a smoother control over its reactance, in response to system parameter variations. In a practical TCSC implementation several compensators may be connected in series to obtain the desired voltage rating and operating characteristics. The TCSC has 20% of line reactance (i.e. 0.2 X), where X is the reactance of the transmission line where the TCSC is installed, without violating the thermal rating limit of the particular line [25].

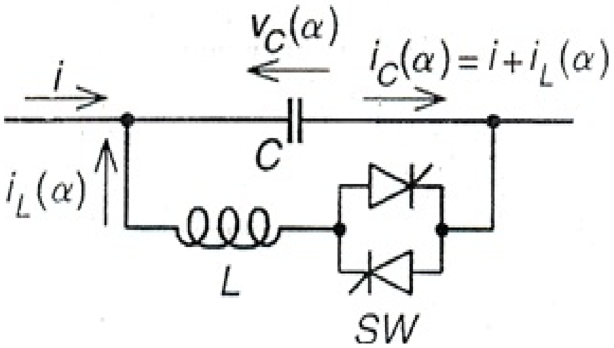

Fig.1 Basic TCSC model

X_C = fixed capacitive impedance
X_L (α) = variable inductive impedance
X_{TCSC} = reactance of the TCSC

$$X_{TCSC}(\propto) = \frac{X_C\, X_L\,(\propto)}{X_L\,(\propto) - X_C} \tag{1}$$

Where

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

$$X_{Lmin} \le X_L(\propto) \le X_{Lmax} \tag{2}$$

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

$$i_L(\propto) = \frac{1}{L}\int_{\propto}^{\omega t} V(t)dt \tag{3}$$

$$i_L(\propto) = \frac{V_m}{\omega L}\ (\sin\omega t - \sin\alpha) \quad (4)$$

Considering the fundamental current,

$$i_L(\propto) = \frac{V_m}{\omega L}\ \left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right) \quad (5)$$

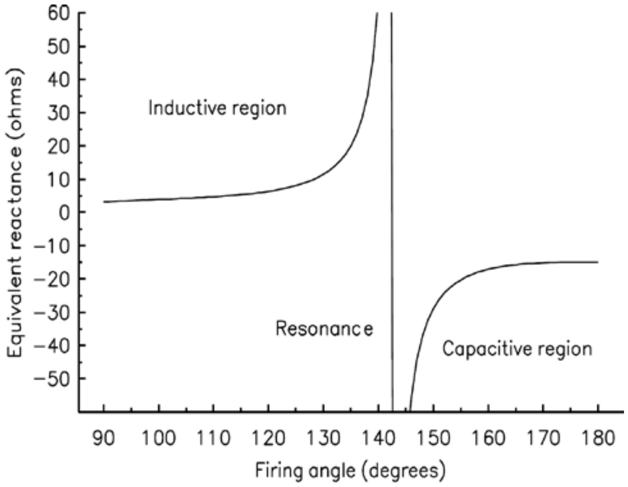

Fig.2 Relationship Between Firing Angle (α) and X_{TCSC}

3 BAT Algorithm

Bat Algorithm (BAT) is a nature inspired Meta heuristic algorithm which is developed by Xin-She Yang in 2010. Meta heuristic 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. This algorithm is based on the echolocation behavior 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. The rules are given in [26].

3.1 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.

3.2 Movement of Virtual Bats

The rules for modifying the positions x_{ii} and velocities v_{ii} of the virtual bats are given as (6)

$$f_i = f_{min} + (f_{\max} - f_{\min})\beta \quad (6)$$
$$v_i^t = v_i^{t-1} + \left(x_i^t - x_*\right) f_i$$
$$x_i^t = x_i^{t-1} + v_i^t$$

Where, $\beta \in [0, 1]$ is a random vector drawn from an identical distribution. Here x_o 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 (7)

$$x_{new} = x_{old} + \epsilon A^t \quad (7)$$

where $\varepsilon \in [-1, 1]$ is a random number, while $A^t = \langle A_i^t \rangle$ 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 (BAT) can be iterating as the pseudo code shown in Fig: 3. [27]

BAT Algorithm

```
Objective function $f(x)$, $x = (x_1, x_2, ..., x_d)^T$
Initialize the bat population $x_{ii}$ ($ii = 1, 2, ..., n$) and $v_{ii}$
Define pulse frequency $f_{ii}$ at $x_{ii}$
Initialize pulse rates $r_{ii}$ and the loudness $A_{ii}$
while ($t$ <Max number of iterations)
Generate a new solution by changing frequency,
And modifying velocities and solutions [equations (2) to (4)]
if (rand > $r_{ii}$)
Select a best solution in the available solutions
Create a local solution around the selected best solution
end if
Create a new solution by flying randomly
if (rand < $A_{ii}$ & $f(x_{ii}) < f(x_o)$)
Accept the new solutions
Increase $r_{ii}$ and reduce $A_{ii}$
end if
Rank the bats and find the current best $x_o$
End while
Post process results and visualization
```

Fig.3 Pseudo code of the bat algorithm (BAT).

3.3 Loudness and Pulse Emission

The loudness A_{ii} and the rate of pulse emission r_{ii} 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 (11)

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

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 A_0 can typically be (1, 2), while the initial emission rate r_i^0 can be (0, 1).

4 Problem Formulation

The objective function for the OPF reflects the costs associated with the real power generation of the generator buses in the power system. The quadratic cost function is given as:

$$C = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (8)$$

Where P_{Gi} is the amount of generation in megawatts at generator bus i.

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

The objective function for the entire power system can then be written as the sum of the quadratic cost function of all the generator buses.

$$F(x) = \sum_{i=1}^{ng} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \quad (9)$$

Where ng = no.of generator buses

Subject to following equality and inequality constraints

$$\sum_{i=1}^{N} P_{Gi} = \sum_{i=1}^{N} P_{Di} + \quad P_L \quad (10)$$

Voltage constraint:

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

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

Real power generation limit:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (12)$$

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

Where P_L is the active power loss in the system, P_{Gi} is the active power generation at bus i, P_{Di} is the power demand at bus i, N and ng are the number of buses and no of generators in the system respectively. Here the main objective is to find the best location for the TCSC device in the power system. In the BAT search algorithm, placement of the TCSC in a line is considered as a variable along with the real power generation of the generator buses as other variables. BAT based OPF is run and the active power losses in the system with the TCSC placed in each line is calculated. Further the line corresponding to minimum active power loss is identified as the best location of the TCSC of a given bus system. In this paper the size of the TCSC is consider to be 20% of the line reactance.

5 Results and Discussion

In order to demonstrate the performance of the BAT Algorithm in Optimal Power Flow with the TCSC device, 5 bus test system, the IEEE14 bus system and the modified IEEE30 bus systems have been considered. An OPF program using the BAT algorithm approach has been written using MATLAB. In this paper, a 5-bus test system, the IEEE 14 bus system and the modified IEEE 30 bus systems have been considered to demonstrate the effectiveness and robustness of algorithm without and with the TCSC and the results have been presented and analysed. The input parameters of BAT Algorithm for the test system are given in Table 1.

Table 1

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

5.1 For 5 BUS System

In 5-bus test system, bus 1 is considered as slack bus, while bus 2 is taken as generator bus and other buses are load buses. The load is considered to be fixed and it is 205MW. Initially, the optimal power flow solution i.e. active power generation, cost and power loss for 5-bus system are calculated using GA, DE methods and the same is implemented for the proposed BAT algorithm method without the TCSC. Next, for the same system the optimal power flow solution is obtained using GA, DE method and BAT algorithm method with the TCSC. The active power generation and power loss for 5 bus test system without and with the TCSC is shown in Table 2. The results given in Tables 3 indicate that the TCSC placed at Line no 1 gives low losses as compared with all the other locations. So it is clear that the best location for the TCSC is line no 1 which is connected between bus no1 and bus no2. Table 4 represents the bus voltage of the network without TCSC and with TCSC. From Table 4, it is clear that the voltage profiles have been improved because of the TCSC. Table 5 indicates comparison of the real power generation, real power losses and reactive power losses using the Genetic algorithm, the Differential Evaluation and the BAT algorithm based optimal power flow. From Table 5 it is observed that by using BAT Algorithm based Optimal Power Flow incorporating TCSC gives fewer losses.

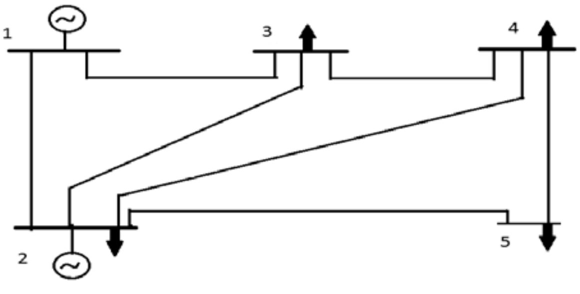

Fig.4. 5 bus test system

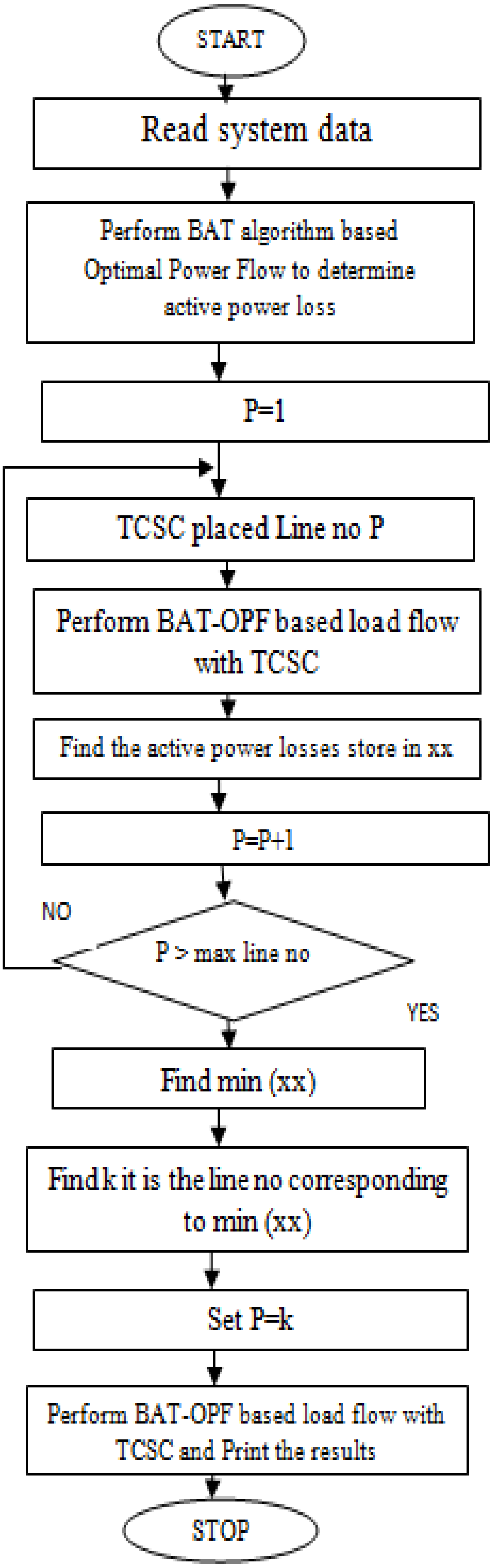

Fig.5. Flow chart for optimal placement of TCSC.

Table 2
Comparison of OPF solution for 5 bus system using the BAT Algorithm without and with the TCSC

S.No	Parameter		BAT-OPF without TCSC	BAT-OPF with TCSC (1-2)
1	Real power generation (MW)	PG1	166.4235	165.1819
		PG2	50.2965	50.2965
2	Total real power generation (MW)		216.7200	215.4784
3	Total real power loss (MW)		11.720	10.4784
4	Total reactive power losses(MVAR)		20.6448	16.1042

Table 3
Incorporation of TCSC Model in BAT-OPF in Different Locations in 5 bus system

S.No	TCSC Location		Total real power loss in MW
	Line No	Connected between *(SB-EB)	
1	Line 1	(1-2)	10.4784
2	Line 2	(1-3)	11.9760
3	Line 3	(2-3)	11.6422
4	Line 4	(2-4)	11.6596
5	Line 5	(2-5)	11.6081
6	Line 6	(3-4)	11.8185
7	Line 7	(4-5)	11.7228

*SB- Starting Bus No
*EB- Ending Bus No

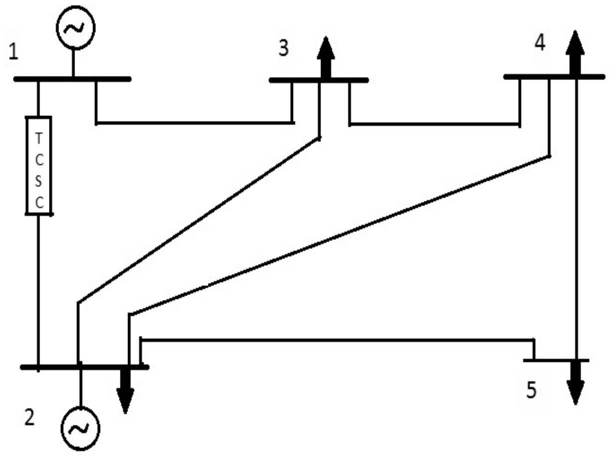

Fig.6. 5 bus test system with TCSC connected between bus no1 and bus no2

Table 4
Comparison of bus voltages and angles for 5 bus system using BAT- OPF without and with TCSC

Bus No.	BAT-OPF without TCSC		BAT-OPF with TCSC(1-2)	
	*VM (volts)	Voltage angle (deg)	*VM (volts)	Voltage angle (deg)
1	1.06	0	1.06	0
2	1	-3.0409	1.0354	-0.2799
3	0.9256	-4.8764	0.9557	-2.7131
4	0.9166	-5.4226	0.9586	-3.0733
5	0.9113	-6.061	0.95	-3.269
6			1.0337	-4.1125

*VM=Voltage Magnitude

Table 5
Comparison of Power Flow solution for 5 bus system using BAT, DE, GA without and with TCSC

	Power Flow Solution	Total Real Power Generation in MW	Total Real Power Losses in MW	Total Reactive Power Losses In MVAR
GA-OPF	Without TCSC	218.2030	13.203	25.0972
	With TCSC	218.1152	13.115	24.8040
DE-OPF	Without TCSC	218.1809	13.180	25.0308
	With TCSC	218.1048	13.104	24.712
BAT-OPF	Without TCSC	216.7200	11.720	20.6448
	With TCSC	215.4784	10.478	16.1042

5.2 For IEEE 14 BUS System

In the IEEE 14 bus system bus no 1 is considered as a slack bus and bus no.s 2,3,6,8 are considered as PV buses all other buses are consider as load buses. This system has 20 interconnected lines. The demand is taken as 259.3MW. The results have been presented and analysed using MATLAB.

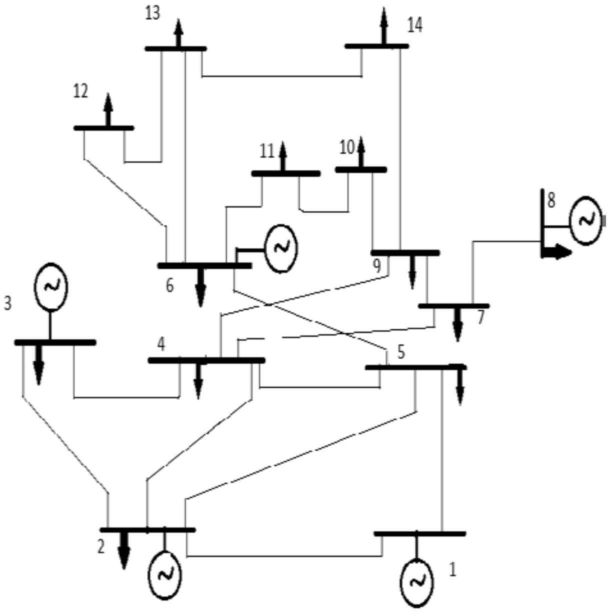

Fig.7 IEEE 14 bus system

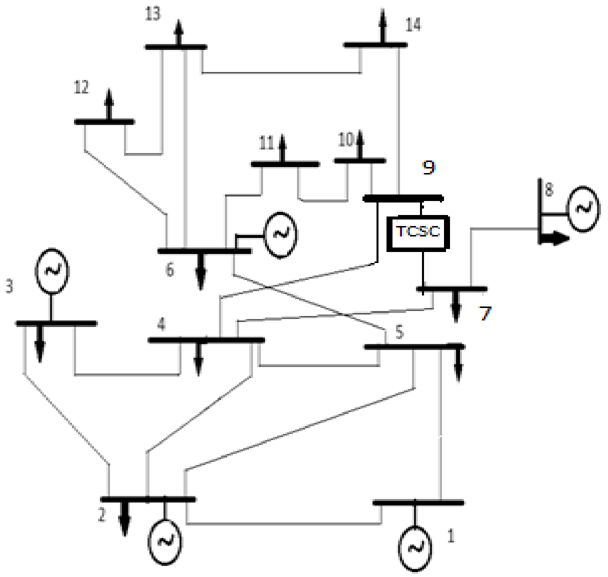

Fig.8 IEEE 14 bus system with TCSC

Table 6
Incorporation of the TCSC Model in BAT-OPF in 5 best Locations in the IEEE 14 bus system

S.No	TCSC Location		Total real power loss in MW
	Line No	Connected between *(SB-EB)	
1	Line 4	(1-5)	5.2972
2	Line 9	(4-7)	5.3424
3	Line 11	(4-9)	5.3278
4	Line 12	(7-9)	5.2659
5	Line 17	(9-14)	5.3271

Table 7
Power Flows for the IEEE 14 bus system without and with the TCSC placed between bus no.7 and bus no.9 (line 12)

	Power Flow Solution	Total Real Power generation (MW)	Total Reactive Power generation (MVAR)	Total Real Power losses (MW)
GA-OPF	Without TCSC	265.3294	84.1035	6.0294
	With TCSC	265.1774	83.0117	5.8774
DE-OPF	Without TCSC	265.1807	83.5858	5.8807
	With TCSC	265.0330	82.5036	5.733
BAT-OPF	Without TCSC	264.2167	80.3974	4.9167
	With TCSC	263.9577	78.8531	4.6577

Table 8
Comparison of reallocation of Real power generation of Generator busses in various methods

PV Bus NO		1	2	3	6	8
Generation limits in MW	Min	10	20	20	10	10
	Max	160	80	50	35	30
Real Power Generation in MW using GA-OPF	With out TCSC	136.614	41.830	21.88	35.0	30.0
	With TCSC	136.462	41.830	21.88	35.0	30.0
Real Power Generation in MW using DE-OPF	With out TCSC	135.269	41.016	23.89	35.0	30.0
	With TCSC	135.121	41.016	23.89	35.0	30.0
Real Power Generation in MW using BAT-OPF	With out TCSC	126.323	32.097	43.11	32.7	30.0
	With TCSC	126.064	32.097	43.11	32.7	30.0

The results given in Tables 6 indicate that the models of the TCSC placed at Line no12 gives low losses as compared with all the other locations. So it is clear that the best location for the TCSC is line no.12 which is connected between bus no.7 and bus no.9.

Table 9
Comparison of bus voltages for 14bus system using BAT-OPF without and with TCSC

Bus No.	BAT-OPF without TCSC		BAT-OPF with TCSC(TCSC placed between buses 7 -9)	
	*VM (volts)	Phase Angle	*VM (volts)	Phase Angle
1	1.06	0	1.06	0
2	1.045	-2.6123	1.045	-2.5789
3	0.9967	-6.463	1.01	-6.5186
4	1.0108	-5.3756	1.0347	-5.6818
5	1.0191	-4.5074	1.0415	-4.7939
6	1	-6.6928	1.07	-6.6704
7	0.9885	-5.7258	1.0462	-6.3289
8	1	-2.6613	1.09	-3.6728
9	0.9712	-7.8878	1.036	-7.3714
10	0.9681	-8.0029	1.0344	-7.5297
11	0.9799	-7.4917	1.0484	-7.2207
12	0.9831	-7.7188	1.0537	-7.5461
13	0.9766	-7.8326	1.0473	-7.6145
14	0.954	-9.0364	1.0227	-8.4994
15			1.0262	-8.4339

*VM= Voltage Magnitude

The active power generation and power loss for the IEEE 14 bus system without and with the TCSC are shown in Table 7. From Table 7 it can be observed that total active power generation required is reduced to 263.9577 MW from 264.2167MW and power loss has been reduced to 4.6577MW from 4.9167MW because of incorporating the TCSC in the BAT Algorithm based OPF. Table 8 indicates the reallocation of real power generations at various generator buses with different optimization techniques like GA, DE and BAT search algorithm. From this table it is clear that with the BAT search algorithm generation values were rescheduled most optimally than the other techniques. Table 9 indicates the voltage profile of IEEE 14 bus system using BAT Algorithm based Optimal Power Flow without and with the TCSC. It indicates that by incorporating the TCSC in the BAT algorithm based OPF voltage profile has been improved. It has shown in Fig.9. From the Fig.10 it has been observed that BAT Algorithm takes less number of generations to converge and gives best results as compared to DE and GA Algorithms.

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