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BHA based Optimal Transformer Tap Settings and TCSC Size in Deregulated Power Market for Transmission Congestion

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Abstract: In a deregulated Power market the transmission congestion is a critical challenge. Transmission congestion management plays a vital role to entertain the desired power transactions without any line outages due to heavy power flow. In this work, a cost free congestion technique is presented through reactive power loss and line flow minimization.For minimum fuel cost the corresponding real power settings are set and it is not altered, for relieving line over loads only the line flows are adjusted. For congestion relief, the control variables are the tap settings in Transformer and locating the size of two thyristor controlled series capacitor (TCSC) are considered.Optimal values of control parameters are attained by applying the simple and natural based intelligence technique ofblack hole algorithm (BHA). The suggested work is validated by testing it in the modified IEEE 30 bustest system,and the really encouraging results are obtained.

KEYWORDS*:* Congestion management, Reactive power loss, Power flow performance index ,Transformer tap settings, TCSC, FACTS, Black hole algorithm.

I. INTRODUCTION

In competitive power markets, large number of bilateral and/or multilateral transactions leads the transmission lines to operate much closer to their thermal limit. At particular operating conditions, when thermal limit violation will be a risk, where it is termed as transmission congestion. Lack of coordination between Generator Companies and Transmission Companies will results in relative decline in investment for transmission systems [2]. By constructing new transmission lines the Congestion can be removed but it needs long time for realisation [1].
Capacity of violation in generators or in transformers or in transmission lines is defined as congestion but normally congestion is used to refer to the line flow limit violation. Due to congestion the voltage collapse and line outage may occur that may leads to serious threats to the power systems security. For the period of congestion, market imbalance and price volatility may occur and the consumers will suffer with the purpose at competitive price to the consumers by supplying power [3]. The additional problem affected by congestion being it forces barriers on existence of novel contracts [4]. Therefore congestion management is a vital problem to be addressed in restructured markets.
Several approaches have been suggested in the literature for congestion management [5]-[7]. Congestion in Transmission is relieved by way of forced lines outage, load curtailment, reschedule in generation, transformer tap settings and operation of FACTS devices [8]-[9]. Amongst the methods mentioned above, usage of FACTS devices and tap settings in transformer are cost free means methods hence they do not include any marginal cost [10]-[11] excepting the capital cost (cost free means methods).

For congestion management and power system control the FACTS devices are been used [12]-[13]. For power flow control Series FACTS devices are comparatively better than shunt FACTS devices. Usage of series FACTS controllers with TCSC will support the governing of power flow in the congestion management. In recent researches, Sensitivity factors based methods are tried for the optimal location of TCSC in the congestion management [14]. For congestion relief, the TCSC is a low cost FACTS device hence it's widely used.

In the deregulated power system there will be more Benefits when FACTS devices are located in maximum proper position [15]-[17]. For maximizing the benefits by FACTS devices in congestion managementmany Intelligence methods are applied [18].The newly developed BHA is implemented for congestion management by load curtailment and/or generation reschedule (non cost free methods).

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In this work, to manage the transmission congestion is achieved by adjusting the reactive power loss/line flow in different transmission lines in the system. For reactive power loss/line flow minimization the decision variables are Transformer tap settings and TCSC sizes. The control parameters are diverse in a coordinated manner and enhanced results are achieved.

II. MODELLING OF TCSC

For change in power flow in the transmission line, TCSC series connected FACTS device connected in sequence with the transmission line. For suitable static applications Power injection model of FACTS devices are used likely in congestion management [19]-[20].some amount of real and reactive power will be injected by TCSC into the system therefore it can be represented as PQ elements. The symmetry of the bus admittance matrix will not affected by power injection model is the major advantage. The Nominal Π network of transmission line is used where TCSC is considered as a variable capacitor and connected in series.

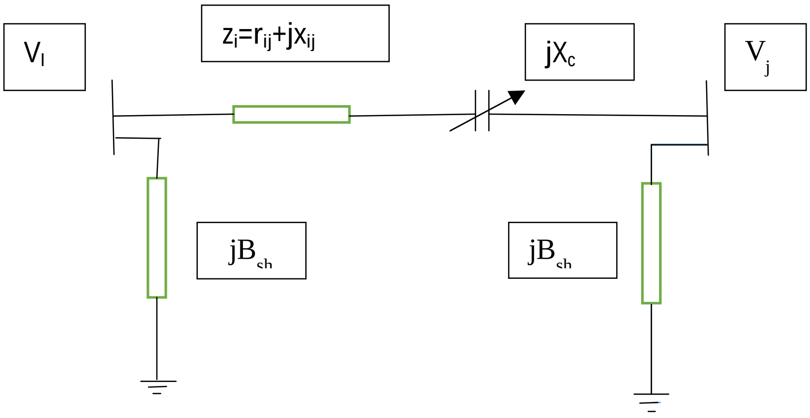

Figure 2.1 Equivalent circuit of a TCSC

The equations (1)-(4) express the exchanges real and reactive power in the system with the presence of TCSC. This injection power which modifies the bus powers only but not the symmetry of bus admittance matrix.

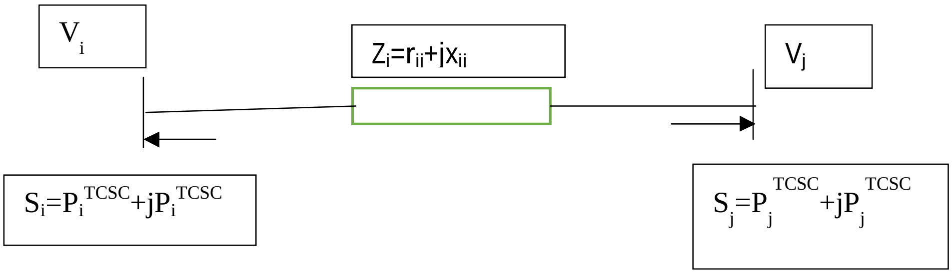

Figure 2.2 Power injection model of TCSC

The real and reactive powers injected at buses ‘*i*’ and ‘*j*’ are

$$P_i^{TCSC} = V_i^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i-\delta_j) + \Delta B_{ij}\sin(\delta_i-\delta_j)] \qquad (1)$$

$$Q_i^{TCSC} = -V_i^2\Delta B_{ij} - V_iV_j[\Delta G_{ij}\sin(\delta_i-\delta_j) - \Delta B_{ij}\cos(\delta_i-\delta_j)] \qquad (2)$$

$$P_j^{TCSC} = V_j^2\Delta G_{ij} - V_iV_j[\Delta G_{ij}\cos(\delta_i-\delta_j) - \Delta B_{ij}\sin(\delta_i-\delta_j)] \qquad (3)$$

$$Q_j^{TCSC} = -V_i^2\Delta B_{ij} + V_iV_j[\Delta G_{ij}\sin(\delta_i-\delta_j) + \Delta B_{ij}\cos(\delta_i-\delta_j)] \qquad (4)$$

In the above given equations shows the change in conductance (ΔG_{ij}) and Susceptance (ΔB_{ij}) of the line in which TCSC is located are given as:

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_c - x_{ij})}{(r_{ij}^2 + x_{ij}^2)[r_{ij}^2 + (x_{ij} - x_c)^2]} \qquad (5)$$

$$\Delta B_{ij} = \frac{x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)[r_{ij}^2 + (x_{ij} - x_c)^2]} \qquad (6)$$

III. BLACK HOLE PHENOMENON

In the eighteen century the concept of black holes are introduced by John Michell and Pierre Laplace. By integrating Newton’s law they identified the absence of star but, at the period absence of star was not known as black hole. Later in 1967, John Wheeler, an American physicist who first named the phenomenon of mass collapsing or the absence of star as a black hole. A black hole in the space is what is left when a star or the massive sized planet collapses.

The black hole gravitational power is too high therefore the light also cannot escape from it. In the boundary of the black hole anything it crosses will be swallowed and vanishes. In space the event horizon will be a sphere-shaped boundary of a black hole. The radius of the event horizon is termed as the Schwarzschild radius. At this radius of the black hole, the escape speed is equal to the speed of light, and even light cannot escape once it passes through. The Schwarzschild radius is calculated by the following equation:

$$R = \frac{2GM}{c^2} \quad (6)$$

Where,
G gravitational constant,
M mass of the black hole
Cspeed of light

If anything moves close to the event horizon it will be absorbed into the black hole and permanently disappear. The schematic view of black hole in the space shown in Fig. 3.1

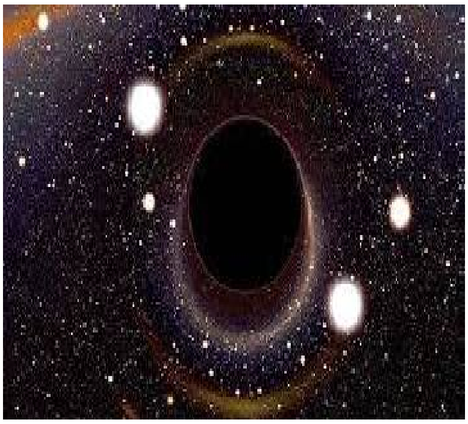

Figure 3.1BLACK HOLE ALGORITHM

The BH algorithm is a population-based optimization method that has some common features with other population-based methods. As with other population-based algorithms, a population of candidate solutions to a given problem is generated and distributed randomly in the search space.

The population-based algorithms evolve the created population towards the optimal solution via certain mechanisms. For example, the evolving is done by mutation and crossover operations in GAs, while in PSO, this is done by moving the candidate solutions in the search space using the local and global best particle locations, which are updated during the iterative process. In the proposed BH algorithm the evolving of the population is done by moving all the candidates towards the best candidate in each iteration, namely, the black hole and replacing those candidates that enter within the range of the black hole by newly generated candidates in the search space.

In this method each solution point in the problem space is represented as a star. In the BH algorithm a population of stars is considered and the best star among all the stars in the population at each iteration is selected as the black hole. The creation of the black hole is not random and it is one of the real candidates of the population. Then, all the candidates are probabilistically moved towards the black hole based on their current location and their cost. The details of the BH algorithms are as follows:

Like other population-based algorithms, in the proposed black hole algorithm (BH) a randomly generated population of candidate solutions – the stars – are placed in the search space of some problem or function. After initialization, the fitness function values of the population are evaluated and the best candidate that has the largest fitness value in the population, is selected as the black hole possessing the ability to absorb the surrounding stars and the rest as normal stars. After initializing the black hole and stars, the black hole starts absorbing the stars around it and all the stars start moving towards the black hole. The absorption of stars by the black hole is formulated as follows:

$$x_i(t+1) = x_i(t) + rand\ (0,1)(x_{BH} -, x_i(t)) \qquad (7)$$

Where

$x_i(t)$ location of the i^{th} star at iteration t;

$x_{i(t-1)}$ location of the i^{th} star at iteration $t-1$;

x_{BH} location of the black hole in the search space;

rand random number in the interval [0, 1].

While moving towards the black hole, a star may reach a location with higher fitness than that of the black hole. In such a case, the black hole moves to the location of that star and vice versa. Then the BH algorithm will continue with the black hole in the new location and then stars start moving towards this new location.

In addition, there is a probability of crossing the event horizon while moving stars towards the black hole. Every star that crosses the event horizon of the black hole will be sucked by the black hole. Every time a candidate (star) dies – it is sucked in by the black hole – another candidate solution (star) is born and distributed randomly in the search space and starts a new search. This is done to keep the number of candidate solutions constant. The next iteration takes place after all the stars have been moved.
The radius of the event horizon in the black hole algorithm is calculated using the following equation.

$$R = \frac{f_{BH}}{\sum_{i=1}^{N} f_i} \qquad (8)$$

Where,

f_{BH} is the fitness value of the black hole and f_i is the fitness value of the i^{th} star. N is the number of stars. The stars will be collapsed, when the distance between stars and black hole is less than the radius R and new stars will be randomly generated in the search space. The key steps in the BH algorithm are given in pseudo code as follows:
The implementation of BHA is depicted in the flowchart shown in Fig. 3.2.

3.1 PSEUDO CODE FOR BLACK HOLE ALGORITHM:

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Step 1:  Initialize a random population of stars at arbitrary locations in the search space

Step 2:  Calculate the fitness value of every star as a candidate solution

Step 3:  Select the best star with largest fitness values as the black hole
Step 4:  Modify the position of every star  by equation (8)
Step 5:  If a star reaches a position with higher fitness than the black hole, then  interchange their locations.
Step 6: Calculate the R between the black hole and stars
Step 7:  when a star crosses the event horizon of the black hole, create a new star randomly in search space
Step 8: Stop criterion with global best solution
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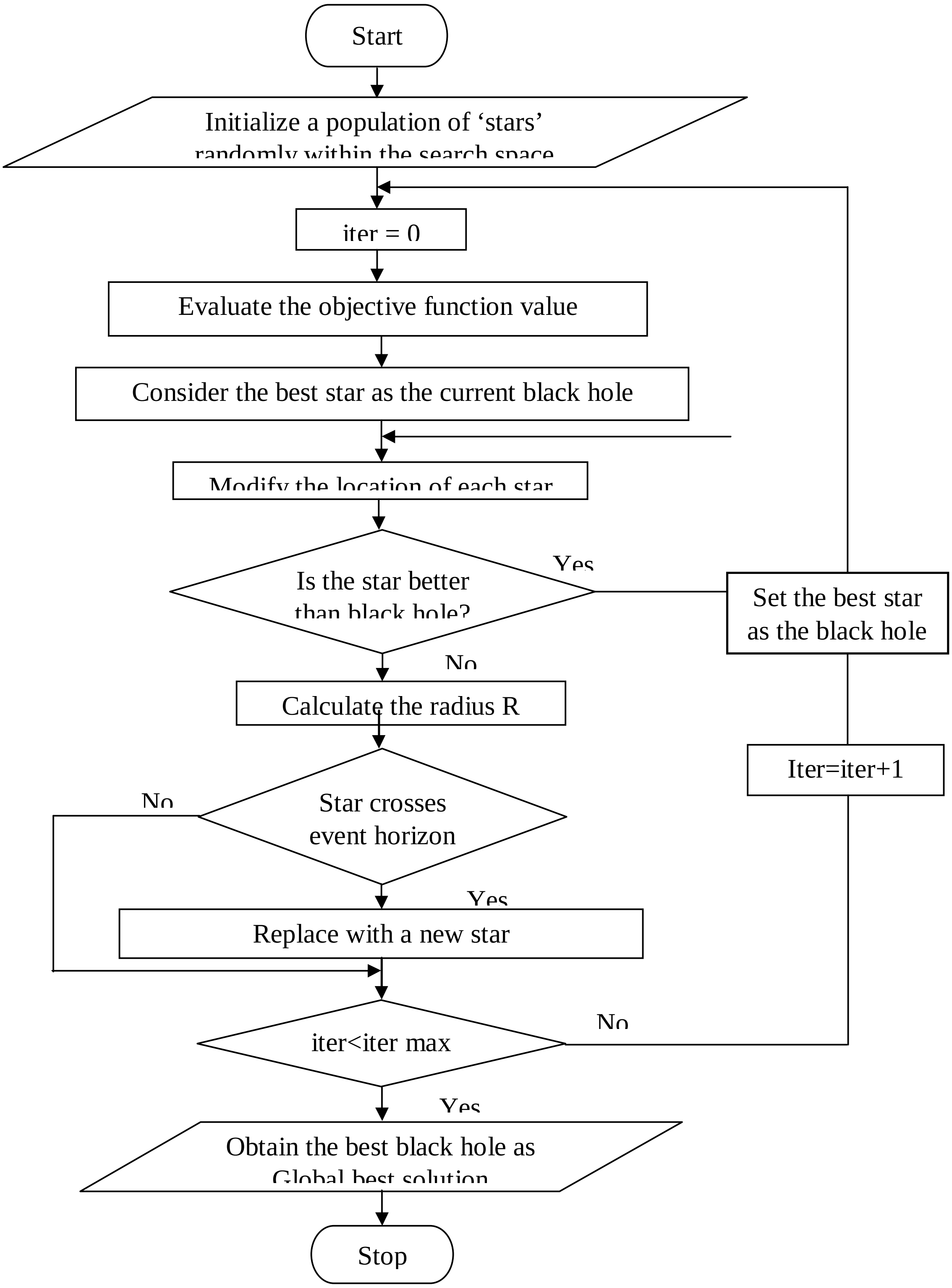

Fig.3.2 Flow chart for Black Hole Algorithm

IV. CONGESTION MANAGEMENT PROBLEM FORMULATION

Congestion management is attained either by minimizing total reactive power loss in the system or by minimizing the MVA flow through overloaded lines. Sum of reactive power flow through all the lines in the system is taken as the objective value for location of TCSC in the first case and power flow performance index (PI) is the objective in the second case. In the system TCSCs are located so that the total reactive power loss/PI value is minimum.

To minimize the total reactive power loss or PI value is the objective of this work for congestion relief. So the objective functions can be written as:

$$min \sum_{k=1}^{NL} Q_L^k = B_k[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \qquad (9)$$

$$min \sum_{k=1}^{NL} \frac{w}{2n}\left(\frac{MVA_k}{MVA_k^{lim}}\right)^{2n} \qquad (10)$$

WhereQ_L^k is the reactive power loss in line ‘*k*‘;

NL is total number of lines;

$B_k$is the susceptance of line ‘*k*‘;

Vi and *Vj*are the magnitudes of bus voltages at bus ‘*i*‘ and bus ‘*j*‘;

$\delta_i and\ \delta_j$are angles of bus voltages at bus’*i*‘ and bus’_*j*‘;

MVA_k *is* the apparent power flow through line *k*‘;

$MVA_k^{lim}$is the apparent power flow limit. Equal weightage is given to all lines (the weightage factor _*w*‘is taken as ‘1‘). The value of power component ‘*n*‘ is considered to be ‘1‘ in this study.

Subject to:

$$P_i(\delta, V) - P_{Gi} + P_{Di} = 0, for\ \ node\ i \qquad (11)$$

$$Q_i(\delta, V) - Q_{Gi} + Q_{Di} = 0, for\ \ node\ i \qquad (12)$$

Apparent power flow limit

$$MVAij(\delta, V) \le MVA_{ij}^{max} \qquad (13)$$

Power generation limit

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \qquad (14)$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} (15)$$

TCSC reactance limit

$$x_c^{min} \le x_c \le x_c^{max} \qquad (16)$$

Bus voltage magnitude limit

$$V_i^{min} \le V_i \le V_i^{max} \qquad (17)$$

4.2 Implementation of BHA for congestion management

Each stars in the population is defined as a vector containing the values of control parameters including the size and location of TCSCs. Particle is (*Tp1, Tp2, Tp3, Tp4* , *XTCSC1, LOCTCSC1* , *XTCSC2, LOCTCSC2*) TCSC device is positioned at a possible location (line) and the NR load flow is run and reduction in reactive power loss/PI index (fitness) is observed. This procedure is repeated for all particles in the black holes iteratively. Then the radius of each stars is calculated and they move to some other line in the system (takes new position) with the new stars. The fitness of each stars corresponding to its new position is calculated by running load flow problem. The current fitness is compared with the fitness of the same particle in the previous iteration.

There is a trade-off between the number of stars and the number of iterations of the black holes and each particle fitness value has to be evaluated using a power flow solution at each iteration, thus the number of stars should not be large because computational effort could increase dramatically. Stars of 10, 20 and 50 particles are chosen as an appropriate population sizes.

The suggested method is verified in IEEE 30 bus test system [22]. The real power settings correspond to optimal power generation cost [23]. The real power settings are not changed to keep the system operating conditions the most economical one only the line flows are adjusted so as to avoid line congestions. The test system has 6 generator buses, 24 load buses and 41 transmission lines. Four of the lines (11, 12, 15, 36) have tap changer transformers.

The real power settings are optimized for minimum fuel cost but these settings results in line flow congestion in line number'1'connected between buses 1-2. The maximum limit of this line is 130 MVA and apparent power flow through this line when fuel cost isminimized is 113.12 MVA. When power flow through a line exceeds 80% of its limit, the line is treated to be congested. Power flow through the line is 88.78% of its limit that the congestion is clear. Even though the fuel cost is optimized, the system is not under secured conditions for operation in deregulated environment. Optimal power flow in deregulated market should take into account the line flow limits as a vital constraint.

Four transformer tap settings and location and size of two TCSCs are taken as control variables for optimizing the congestion management. There are 4 tap changer transformers and one location and one size for each TCSC accounting 8 control variables. The upper and lower bounds of the 8 control parameters are listed in table 2. The problem is approached in two different ways as explained in the following sections.

Table 2. Allowable range of control variables

Sl No	Control Variable	Range
1	Tap setting (T_{pi})	(0.9)-(1.1)
2	TCSC reactance (x_c)	(-0.8x_{ij})-(0.2x_{ij})
3	TCSC location (LOC_{TCSC})	(1)-(41)

Case A: Reactive power loss minimization approach

Increased reactive power flow is an indication of increased MVA power flow (congestion) in transmission lines. Congestion can be relieved by minimizing the reactive power loss. TCSC is used to change the line reactance and thereby the line power flow gets changed. The values of control variables are so set that the total reactive power loss in the system is minimized. The algorithm is run a number of times to obtain the most suitable values for the control variables. The optimal values of transformer tap settings and TCSC location and size are as given in table 3. The total reactive power (objective function value) is reduced from 38.9560 MVAR to 31.7446 MVAR after the optimization of 4 trans-former tap settings and sizes of 2 TCSCs.

Table 3.Global best parameter values

Sl No	Control variable	Initial value	Global best value
1	T_{p11}	0.978	1.0234
2	T_{p12}	0.969	1.0013
3	T_{p15}	0.932	0.9001
4	T_{p36}	0.968	0.8934
5	Level of compensation of TCSC$_1$	----	-0.6923
6	Level of compensation of TCSC$_2$	----	-0.8621
7	Location of TCSC$_1$	----	2-4
8	Location of TCSC$_2$	----	1-3

The power flow results corresponding to optimal values of control parameters are shown in table 3. The reduction in reactive power loss after installation of TCSCs helps the system to get relieved from congestion. It is evident that total reactive power loss is from 34.78 MVAR to 30.89 MVAR. It may be observed that the power flow through line '1'between buses 1-2 was 114.78 MVA before congestion is managed. Now, the line flow is only 90 MVA that is congestion is relieved. The change in line flow pattern does not violate the limit of any line in the system.

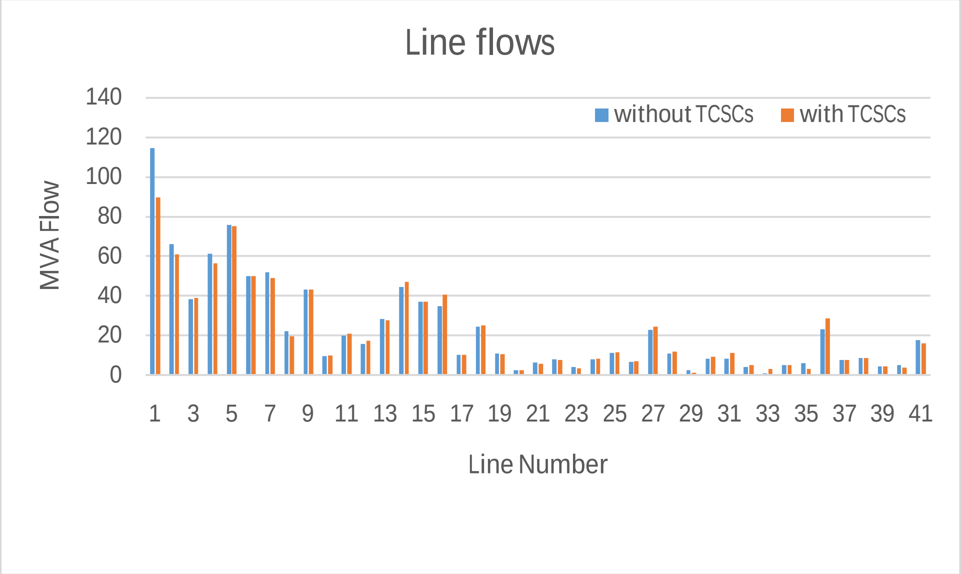

Figure 4. Line flows before and after placement of TCSC (case A)

Case B: Power flow performance index approach

In a deregulated environment, power flow through some of the transmission line may near the thermal limit while other lines might be carrying less amount power due to large number of transactions. The overloaded lines are prone to congestion. Power flow pattern is changed to alleviate congestion by controlling tap changer settings and TCSC sizes. The optimal values of control variables are the ones that minimize the PI value to the most optimal level. The BHA after several runs, identifies the most suitable value of control variables as shown in table 4. It may be noted that the optimal control variable values are different from the values obtained in reactive power reduction approach.

Table 4. Global best parameter values

Sl No	Control variable	Initial value	Global best value
1	T_{p11}	0.978	0.9127
2	T_{p12}	0.969	0.9745
3	T_{p15}	0.932	0.8234
4	T_{p36}	0.968	0.8500
5	Level of compensation of $TCSC_1$	----	-0.5623
6	Level of compensation of $TCSC_2$	----	-0.7859
7	Location of $TCSC_1$	----	2-3
8	Location of $TCSC_2$	----	16-17

The line flows before and after the optimization process are com-pared in figure 5. Limit of line 1-2 was carrying 114.78 MVA and it is reduced to 95.549 MVA. It can be seen from the figure that all the lines are carrying less power than their maximum limit.

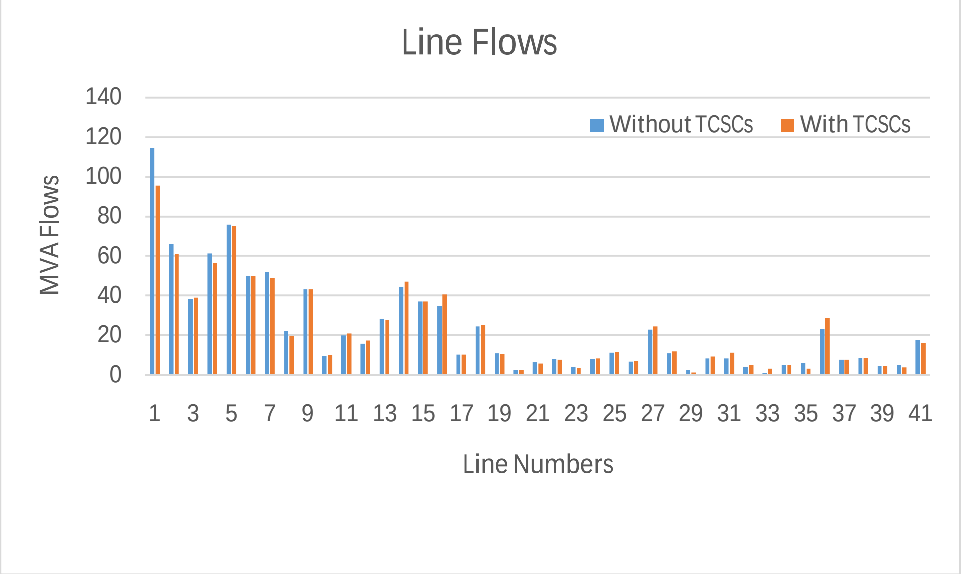

Figure 5. Line flows before and after placement of TCSC (case b)

V. RESULTS AND DISCUSSIONS

This work shows the effectiveness of two cost free congestion management schemes including TCSC devices. Congestion management by these suggested methods do not affect the customer benefits since the real power schedule remains unchanged. It is obvious from the numerical results that the congestion relief is very much encouraging. The system operator can use this method to relive the congestion and all contracted power transactions can be accommodated without violation of line flow limits. Further, all the lines in the system are left with sufficient loading margins and therefore the system becomes capable of transmitting increased amount of power flows. The very purpose of supplying power to consumers at competitive price can be ensured to consumers. This approach, a cost free one, implemented through BHA will be a better alternative to non-cost free methods of congestion management.

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