Optimal Transformer Tap Settings and TCSC Size for Transmission Congestion Management through PSO Algorithm in a Deregulated Power Market

R.Ramachandran, M.Arun, S.Sakthivel

Abstract— Power transmission congestion is a critical challenge in the deregulated energy market. Transmission congestion management is very much necessary for realising all the desired power transactions and to avoid line outages due to heavy power flow. In this paper, a cost free congestion method by reactive power loss/line flow minimization based approach is presented. The real power settings correspond to minimum fuel cost and it is not changed only the line flows are adjusted for relieving line over loads. Transformer tap settings and location and size of two thyristor controlled series capacitor (TCSC) are considered as control variables for congestion relief. Optimal values of control parameters are obtained by implementing the simple and easy to realise swarm intelligence of particle swarm optimization algorithm (PSO). The proposed work is validated by testing it in the medium sized IEEE 30 bus test system and the results obtained are really encouraging.

Index Terms— Transformer tap settings, TCSC, FACTS, Reactive power loss, Congestion management, Particle Swarm Optimization, Power flow performance index.

1 Introduction

In deregulated electricity markets, the transmission lines are operated much closer to their thermal limit due to large number of bilateral and/or multilateral transactions. Under such operating conditions, there is a risk of thermal limit violation what is termed as transmission congestion. Congestion can be alleviated by constructing new transmission lines but it is not straight forward and needs long time for realisation [1]. Moreover there is lack of coordination between GenCos (Generator Companies) and TransCos (Transmission Companies) and it results in relative decline in investment for transmission systems [2].

Congestion is defined as capacity violation of generators or transformers or transmission lines. Now a days the word congestion is used mainly to refer to the line flow limit violation. Congestion is posing threats to the security of power systems as it may cause line outage and voltage collapse. During congestion, price volatility and market imbalance may result and consequently the consumers will suffer and this will shake the very purpose of supplying power at competitive price to the consumers [3]. The other major problem caused by congestion being it imposes barriers on existence of new contracts [4]. Hence congestion management is an important issue to be addressed in restructured markets.

Assistant Proessor, Dept of Electrical Engineering
Annamalai University, Chidambaram, TN, India
E-mail: ramachandran.auee@gmail.com

Assistant Proessor, Dept of Electrical Engineering
Annamalai University, Chidambaram, TN, India
E-mail: arunmano80@gmail.com

Associate Proessor, Dept of Electrical and Electronics Engineering
V.R.S. College of Engineering and Technology, Villupuram, TN, India
E-mail:sithansakthi@gmail.com

Numerous methods have been proposed in the literature for congestion management [5]-[7]. Transmission congestion is relieved by way of generation reschedule, forced outage of lines, load curtailment, operation of FACTS devices and transformer tap settings [8]-[9]. Among the above mentioned methods, use of FACTS devices and control of transformer tap settings are cost free methods since they do not involve any marginal cost [10]-[11] except the capital cost (cost free methods).

FACTS devices are long been used for power system control and congestion management [12]-[13]. Series FACTS devices are relatively better than shunt FACTS devices for power flow control. Use of series FACTS controllers like TCSC will help controlling of power flow for congestion management. Sensitivity based approaches are attempted for optimal location of TCSC for congestion management in recent researches [14]. TCSC is a low cost FACTS device and widely used for congestion relief.

Benefits of FACTS devices are more when they are located in a most suitable position in the power system [15]-[17]. Intelligence techniques are used for maximizing the benefits of FACTS devices in congestion management [18]. The recently developed PSO algorithm is attempted for congestion management by load curtailment and/or generation reschedule (non cost free methods).

In this paper, transmission congestion is managed by optimizing the reactive power loss/line flow through different transmission lines in the system. Transformer tap settings and TCSC sizes are the decision variables for reactive power loss/line flow minimization. The control parameters are varied in a coordinated manner and improved results are obtained.

2 Modelling of TCSC

TCSC is a series connected FACTS device connected in series with the transmission line power flow through which is to be changed. Power injection model of FACTS devices are suitable for static applications like congestion management [19]-[20]. TCSC injects certain amount of real and reactive power into the system and hence it can be represented as PQ elements. The advantage of power injection model is it does not affect the symmetry of the bus admittance matrix. TCSC is considered as a variable capacitor connected in series with the line. Nominal π method of transmission line is used.

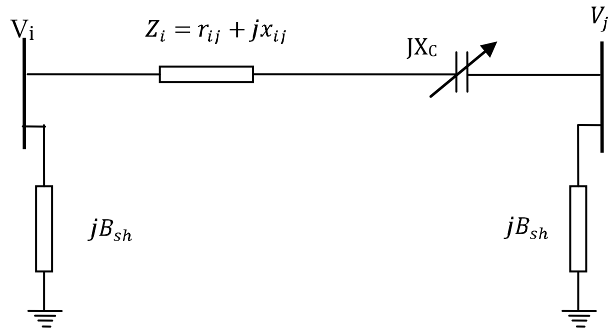

Figure 1. Equivalent circuit of a TCSC

The presence of TCSC exchanges real and reactive power with the system and they are expressed as shown in equations (1)-(4). This power injection modifies only the bus powers not the symmetry of bus admittance matrix.

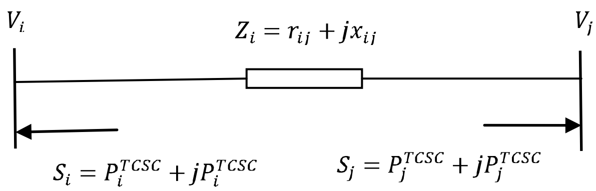

Figure 2. Power injection model of TCSC

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

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

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

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

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

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

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

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

3 PARTICAL SWARM OPTIMIZATION (PSO) ALGORITHM

The concept of PSO was first suggested by Kennedy and Eberhart [21] in 1995. Since its development, PSO has become one of the most promising optimizing techniques for solving global optimization problems. Its mechanism is inspired by the social and cooperative behavior displayed by various species like birds, fish, termites, ants and even human beings. The PSO system consists of a population (swarm) of potential solutions called particles. These particles move through the search domain with a specified velocity in search of optimal solution. Each particle maintains a memory which helps it in keeping the track of its previous best position.

The positions of the particles are distinguished as personal best and global best. In the past several years, PSO has been successfully applied in many research and application areas. It has been demonstrated that PSO gets better results in a faster and cheaper way in comparison to other methods like GA, simulated annealing (SA) etc. The particles or members of the swarm fly through a multidimensional search space looking for a potential solution. Each particle adjusts its position in the search space from time to time according to the flying experience of its own and of its neighbors (or colleagues).

For a *D*-dimensional search space, the position of the i^{th} particle is represented as:

$$X_i = (x_{i1}, x_{i2}, \dots x_{id}, \dots x_{iD}) \quad (7)$$

Each particle maintains a memory of its previous best position which is represented as:

$$P_i = (p_{i1}, p_{i2}, \dots p_{id}, \dots p_{iD}) \quad (8)$$

The best one among all the particles in the population is represented as:

$$P_g = (p_{g1}, p_{g2}, \dots p_{gd}, \dots p_{gD}) \quad (9)$$

The velocity of each particle is represented as:

$$V_i = (v_{i1}, v_{i2}, \dots v_{id}, \dots v_{iD}) \quad (10)$$

The maximum velocity is represented as:

$$V_{max} = (v_{max1}, v_{max2}, \dots v_{maxd}, \dots v_{maxD}) \quad (11)$$

The velocity V_i of each particle is clamped to a maximum velocity V_{max} which is specified by the user. V_{max} determines the resolution with which regions between the present position and the target position are searched. Large values of V_{max} facilitate global exploration, while smaller values encourage local exploitation. If V_{max} is too small, the swarm may not explore sufficiently beyond locally good regions. On the other hand, too large values of V_{max} risk the possibility of missing a good region. At each iteration a new velocity value for each particle is evaluated according to its current velocity, the distance from the global best position. The new velocity value is then used to calculate the next position of the particle in the search space. This process is then iterated a number of times or until a minimum error is achieved. The two basic equations which govern the working of PSO are that of velocity vector and position vector given by:

$$V_{id} = wv_{id} + c_1 rand_1 (p_{id} - x_{id}) + c_2 rand_2 (p_{gd} - x_{gd}) \quad (12)$$

$$x_{id} = x_{id} + v_{id} \quad (13)$$

Here w is the inertia constant, c_1 and c_2 are acceleration constants. They represent the weighting of the stochastic acceleration terms that pull each particle towards personal best and global best positions. Therefore, adjustment of these constants changes the amount of tension in the system. Small values of these constants allow particles to roam far from the target regions before tugged back, while high values result in abrupt movement toward, or past, target regions. The constants $rand_1$, $rand_2$ are the uniformly generated random numbers in the range of (0, 1).

The first part of Eq. (12), wv_{id}, represents particle's previous velocity, which serves as a memory of the previous flight direction. This memory term can be visualized as a momentum, which prevents the particle from drastically changing its direction and biases it towards the current direction. The second part, $c_1 rand_1 (p_{id} - x_{id})$, is called the cognition part and it indicates the personal experience of the particle. We can say that, this cognition part resembles individual memory of the position that was best for the particle. The effect of this term is that particles are drawn back to their own best positions, resembling the tendency of individuals to return to situations or places that were most satisfying in the past. The third part, $c_2 rand_2 (p_{gd} - x_{id})$, represents the cooperation among particles and is therefore named as the social component. This term resembles a group norm or standard which individuals seek to attain. The effect of this term is that each particle is also drawn towards the best position found by its neighbour.

4 Congestion Management Problem Formulation

Congestion management can be achieved 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 former case and power flow performance index (PI) is the objective in the latter case. TCSCs are located in the system such that the total reactive power loss/PI value is minimum.

4.1 Objective function

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

$$min \sum_{k=1}^{NL} Q_L^k = B_k\left[V_i^2 + V_j^2 - 2V_iV_j cos\left(\delta_i - \delta_j\right)\right] \tag{14}$$

$$min \sum_{k=1}^{NL} \frac{w}{2n}\left(\frac{MVA_k}{MVA_k^{lim}}\right)^{2n} \tag{15}$$

Where Q_L^k is the reactive power loss in line 'k'; NL is total number of lines; B_k is the susceptance of line 'k'; V_i and V_j are the magnitudes of bus voltages at bus 'i' and bus 'j'; δ_i and δ_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:

Power balance equations

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

$$Q_i(\delta, V) - Q_{Gi} + Q_{Di} = 0, for\ any\ node\ i \tag{16}$$

If TCSC is located in line between buses 'i' and 'j', the power balance equation at nodes 'i' and 'j' are given by:

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

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

$$P_j(\delta, V) - P_{Gj} + P_{Dj} + P_j^{TCSC} = 0, for\ any\ node\ j$$

$$Q_j(\delta, V) - Q_{Gj} + Q_{Dj} + Q_j^{TCSC} = 0\ for\ any\ node\ j \tag{17}$$

Where P_i is the real power injection in bus 'i'; P_{Gi} and P_{Di} are the real power generation and load at bus 'i'; P_i^{TCSC} is the real power injection due to TCSC at bus 'i'; Q_i is the reactive power injection in bus 'i'; Q_{Gi} and Q_{Di} are the real power generation and load at bus 'i'; Q_i^{TCSC} is the real power injection due to TCSC at bus 'i';

Apparent power flow limit

$$MVA_{ij}(\delta, V) \le MVA_{ij}^{max} \tag{18}$$

Power generation limit

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \tag{19}$$

TCSC reactance limit

$$x_c^{min} \le x_c \le x_c^{\max} \tag{20}$$

Bus voltage magnitude limit

$$V_i^{min} \le V_i \le V_i^{max} \tag{21}$$

4.2 Implementation of PSO for congestion management

4.2.1. Representing an individual:

Each particle in the population is defined as a vector containing the values of control parameters including the size and location of TCSCs.

Particle is (T_{p1}, T_{p2}, T_{p3}, T_{p4} , X_{TCSC1}, LOC_{TCSC1} , X_{TCSC2}, LOC_{TCSC2})

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 swarm iteratively. Then the velocity of each particle is calculated and they move to some other line in the system (takes new position) with the new velocity. The fitness of each particle 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. If the current fitness is better, the current position of the particle is considered as P_{best} otherwise the previous position is retained as the P_{best} and best among the P_{best} of all particles in the swarm is called G_{best}.

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4.2.2. Number of particles:

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

4.2.3. Feasible region Definition:

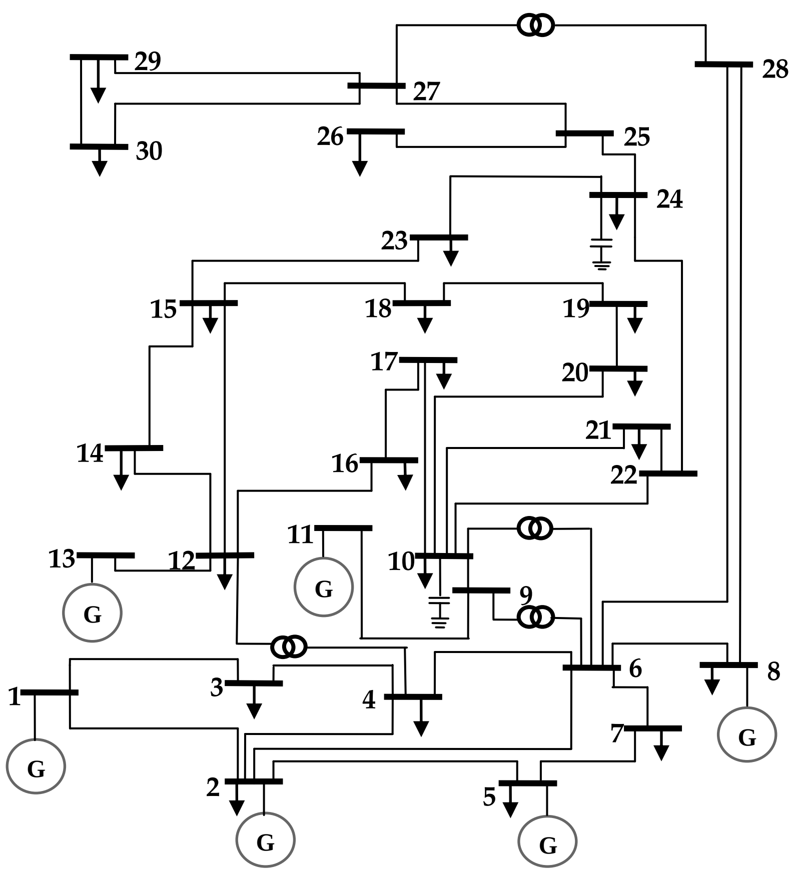
There are several constraints in this problem regarding the characteristics of the power system and the desired congestion relief. Each of these constraints represents a limit in the search space. Therefore the PSO algorithm has to be programmed so that the particles can only move over the feasible region. For instance, the network in Fig. 3 has 4 transmission lines with tap changer transformer. In terms of the algorithm, each time that a particle's new position includes a line with tap setting transformer, the position is changed to the geographically closest line without transformer.

4.2.4. Optimal Parameter Values:

Table 1. Optimal values of PSO parameters

Parameter	Optimal value
Number of particles	50
Inertia weight	0.4
Individual acceleration constant	2.5
Social acceleration constant	2.0
No of iterations	25
Velocity bounds	{-3,7}
$rand_1$	0.3
$rand_2$	0.2

4 Results and Discussions



The proposed method is tested 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. This method is coded in Matlab 7.9 environment and a 2.9 GHz, Core2Duo based computer system is used for the simulation. 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 is minimized is 114.72 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 88.24% 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.

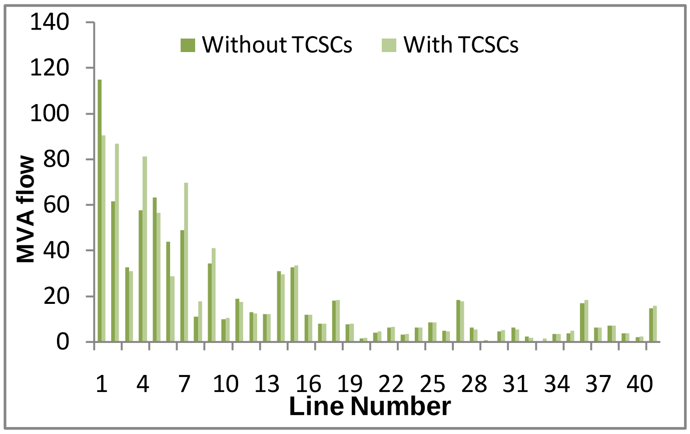
The algorithm is run a number of times to obtain the most suitable values for the control variables. The optimal values of transformer tap settings and TCSC location and size are as given in table 3. The total reactive power (objective function value) is reduced from 38.9560 MVAR to 31.7446 MVAR after the optimization of 4 transformer 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	1.0492
2	T_{p12}	0.969	1.0152
3	T_{p15}	0.932	0.9948
4	T_{p36}	0.968	0.9725
5	Level of compensation of $TCSC_1$	---	-0.6151
6	Level of compensation of $TCSC_2$	---	-0.7990
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.

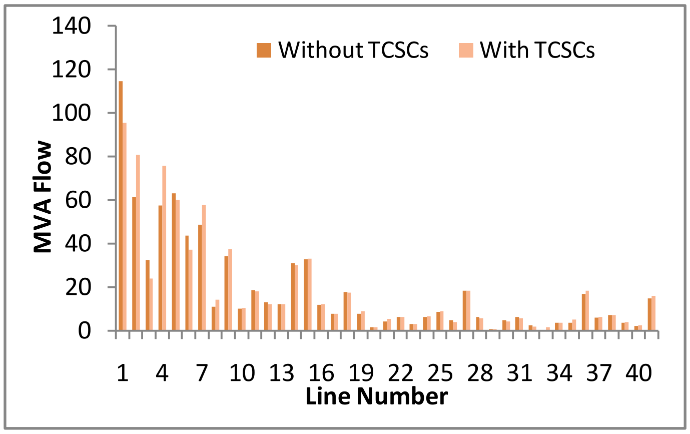
The PSO algorithm, after several runs, indentifies the most suitable value of control variables as shown in table 4. It may be noted that the optimal control variable values are different from the values obtained in reactive power reduction approach.

Table 4. Global best parameter values

Sl. No	Control variable	Initial value	Globalbest value
1	T_{p11}	0.978	0.9882
2	T_{p12}	0.969	1.0240
3	T_{p15}	0.932	0.9653
4	T_{p36}	0.968	0.9433
5	Level of compensation of $TCSC_1$	---	-0.5400
6	Level of compensation of $TCSC_2$	---	-0.7372
7	Location of $TCSC_1$	---	2-3
8	Location of $TCSC_2$	---	16-17

The line flows before and after the optimization process are compared 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)



4 Results and Discussions

This work proves the effectiveness of two cost free congestion management schemes incorporating TCSC devices. Congestion management by these proposed 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 PSO algorithm will be a better alternative to non cost free methods of congestion management. Moreover, the PSO algorithm is simple and it could be implemented easily.

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BIOGRAPHIES

R.Ramachandran received the Degree in Electrical and Electronics Engineering in 2001 and Master Degree in Power Systems Engineering in 2002 both from Annamalai University. He is doing the Ph.D., Degree in Electrical Engineering faculty of Annamalai University, Chidambaram, Tamil Nadu, India. He is as an Assistant Professor in Electrical and Electronics Engineering at the same University. He is interested in the areas of Economic load dispatch, Power system deregulation and Voltage stability improvement.

M.Arun obtained his Bachelor Degree in Electrical and Electronics Engineering in 2001 from Bharathidhasan University, Master Degree in Power Systems Engineering in 2005 and Ph.D. Degree in 2012 both from Annamalai University. He is with the Department of Electrical and Electronics Engineering at Annamalai University Tamil Nadu, India. His research areas of interest are Power System control, Power system deregulation and Voltage stability improvement.

S.Sakthivel received the Degree in Electrical and Electronics Engineering in 1999 from Madras University and Master Degree in Power Systems Engineering in 2002 from Annamalai University. He is pursuing the Ph.D., Degree in Electrical Engineering faculty from Anna University of Technology, Coimbatore, India. He is presently working as an Associate Professor in Electrical and Electronics Engineering at V.R.S.College of Engineering and Technology, Villupuram, Tamil Nadu, India. His research areas of interest are Power System control, Optimization techniques, FACTS, Economic load dispatch, Power system deregulation and Voltage stability improvement.