# Chapter 4

# Optimal placement of Thyristor Controlled Series Compensator (TCSC) for Social Welfare enhancement

## 4.1 Introduction

In economics, social welfare is defined as the total well being of the entire society. Social welfare is non measurable because it involves both objective and value judgments. It is not the same as standard of living but is more like quality of life that includes factors such as the quality of the environment (air, soil, water), level of crime, extent of drug abuse, availability of essential social services, as well as religious and spiritual aspects of life. But, in power system it is defined in following manner: Social welfare is the sum of gross consumers' surplus minus producer costs. In the production and consumption decisions of electricity market, there are two main economic factors: producer and consumer. The producer(GENCOs) produces goods so as to make a profit and consumer consumes to meet their needs so that they can derive the best benefit out of it. In economic terms, the producer profit is known as producer surplus and consumer benefit is termed as consumer surplus. The producer surplus is the difference between the income received from the sale of a good and its production cost. In a competitive market, the producers price their goods at short run marginal cost and produce in a quantity that is demanded in the market. Producer surplus is graphically

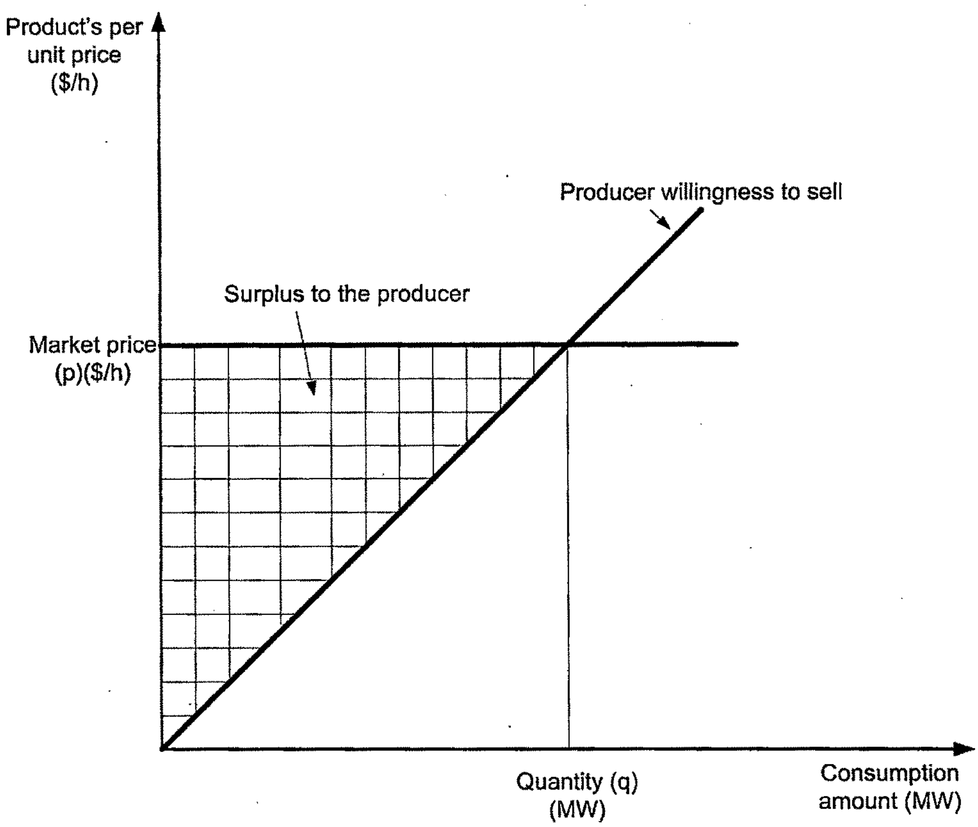


Figure 4.1: Graphical representation of a producer surplus

depicted in Fig. 4.1.

Mathematically it is written as 4.1

$$producer\ surplus = \int_{0}^{q} (p - S(q))dq \tag{4.1}$$

Where,

q= Active power sold,

p=Income received from the sale of active power,

S(q)= Production cost of active power generation,

The consumer surplus is the difference between the values the consumer is willing to pay and what he actually pays. It shows the net gain to consumer of being able to buy all their desired demand at the ruling price, even though they would have been willing to pay higher

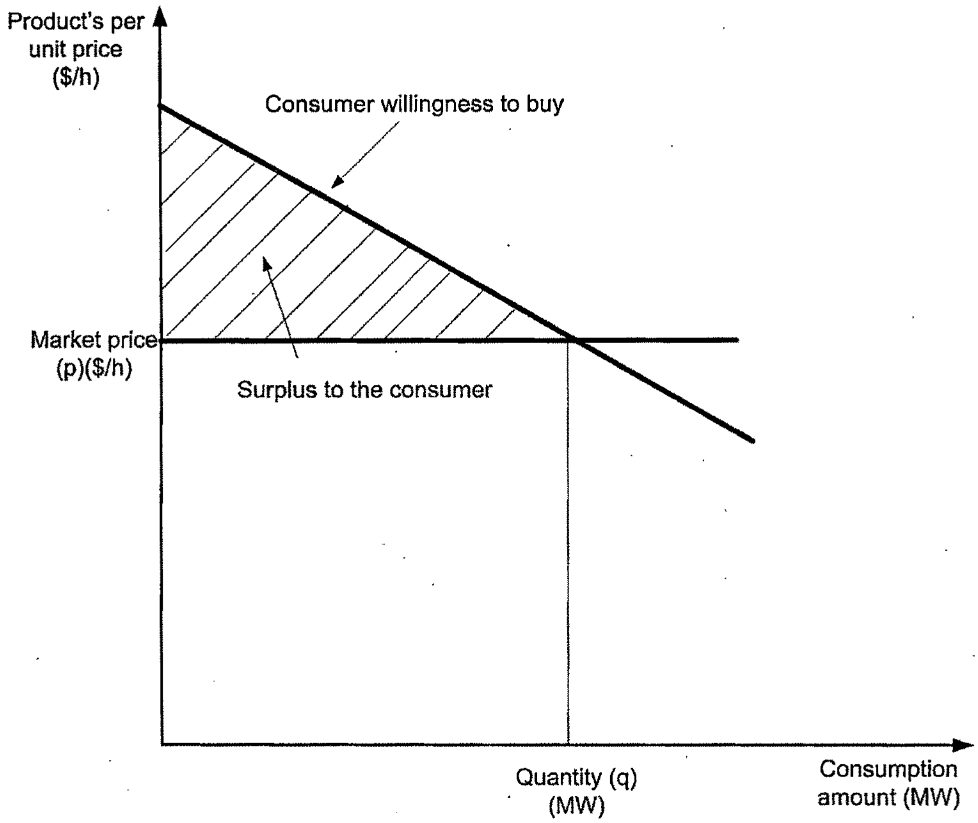


Figure 4.2: Graphical representation of consumer surplus

prices. Consumer surplus is graphically depicted in Fig.4.2.

Mathematically it is written as 4.2

$$consumer\ surplus = \int_{0}^{q} (D(q) - p)dq \tag{4.2}$$

Where,

q= Active power consumed by the consumers,

D(q)=Consumer's willingness to pay (consumers' bid functions)

p=Consumer's actual payment for the consumption of active power

The sum of producer and consumer surplus represents the total value of the market and is termed as social profit or social welfare or social benefit. It is graphically depicted in Fig. 4.3.

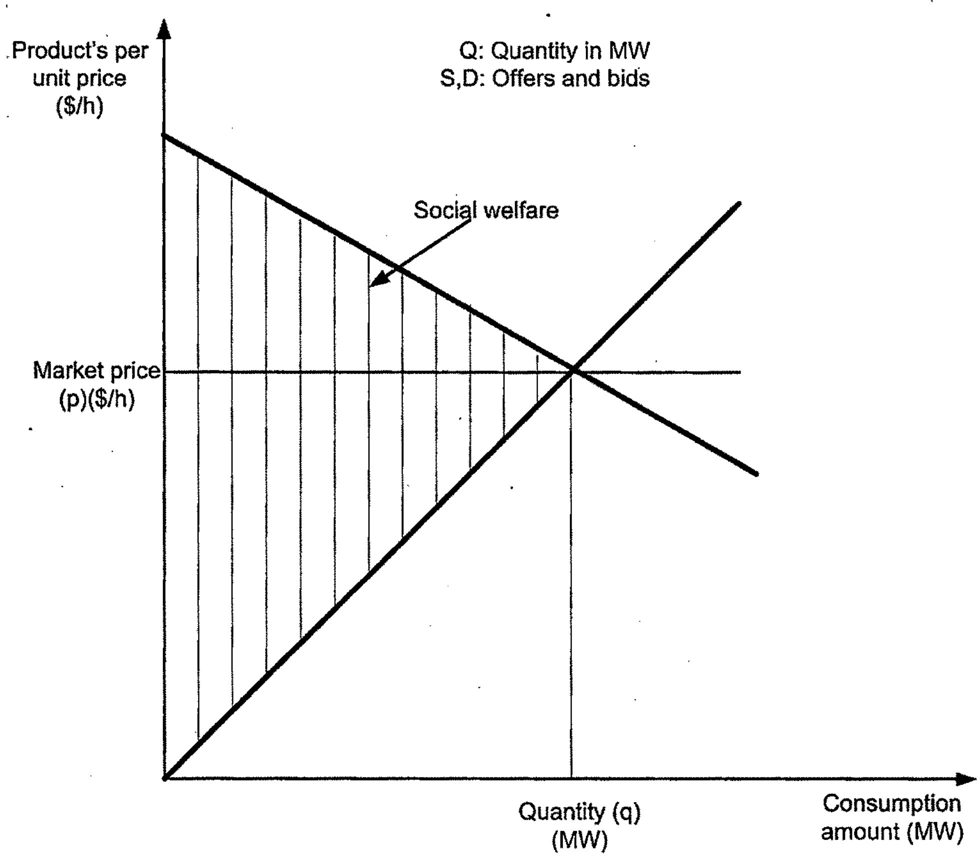


Figure 4.3: Graphical representation of Social Welfare

Mathematically it is written as 4.3

Social Welfare=producer surplus+ consumer surplus

$$Social\ Welfare = \int_{0}^{q} (D(q) - S(q))dq \tag{4.3}$$

The objective of maximizing the social welfare is used to price the goods in the market and this pricing rule is considered to be economically efficient or "pareto" efficient [106]. In this pricing, under the assumption of perfectly competitive market, an equilibrium price is achieved at the point where quantity demanded equals quantity supplied. This is the point where the aggregate production cost (marginal cost of production) intersects with the aggregate willingness to pay curve (demand curve). In electricity market, this equilibrium is distorted if transmission constraints are violated. Other constraints, like voltage limits and generation capacity constraints may also distort the simple market structure. The effect of constraints is to limit the competition and decrease the market and will also transfer the surplus from producer and consumer to someone who regulates the market (like ISO). This give rise to merchandize surplus or the congestion rent. Consider a simple two-bus system with generator at one end and a load at the other end. Let the limit of line connecting this two bus be $P^{limit}$. For this simple case, the line is assumed to be lossless. Let the supply and demand curves are as shown in Fig. 4.4. It is taken from[106].

When constraints are ignored, the equilibrium point is given by the $\lambda^*$ (US$/MWh) and $P^*$ (MW). When the line constraint is considered as shown in Fig.4.5, it will lead to different prices at the two buses. At generator bus, the price falls down and at the consumer bus the price goes up. This results in decrease in both consumer and producer surplus as shown in Fig. 4.5. It is taken from [106].

This will also lead to "dead weight" loss to society. Since, generator and load are compensated by the prices of the respective buses, this leads to the surplus to market operator (ISO). This surplus is known as congestion rent or the merchandize surplus. It is used to compensate for the losses and/or to reinforce the transmission grid or transfer to the participants based on market rules. The price and quantity can be determined by solving the optimization problem with the objective of social welfare maximization subject to power

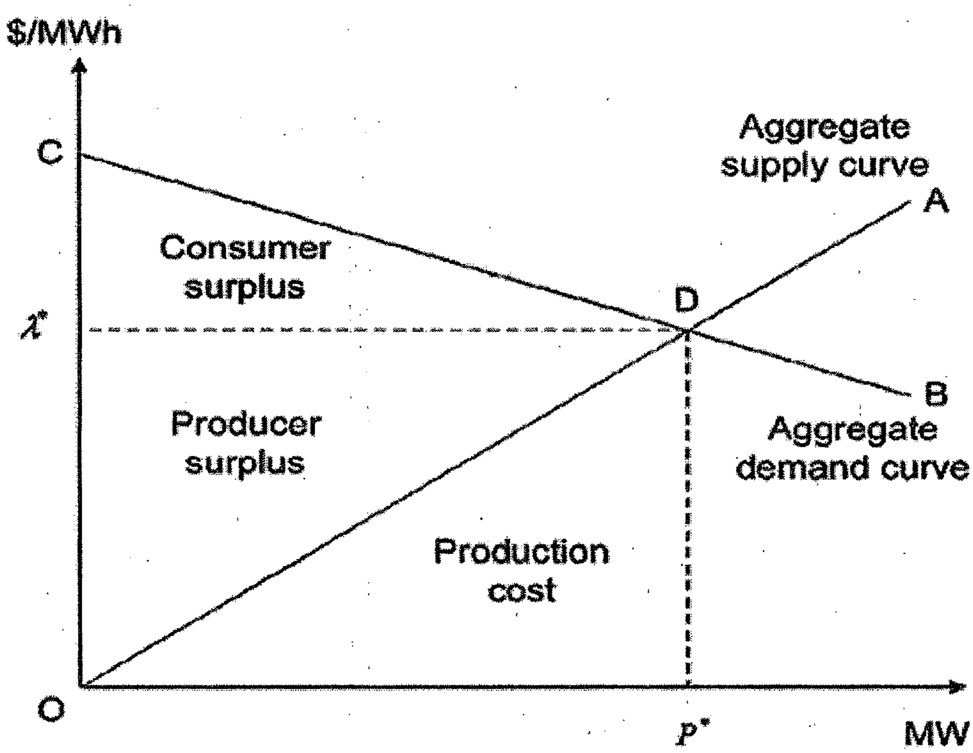


Figure 4.4: consumer and producer surplus under unconstrained case

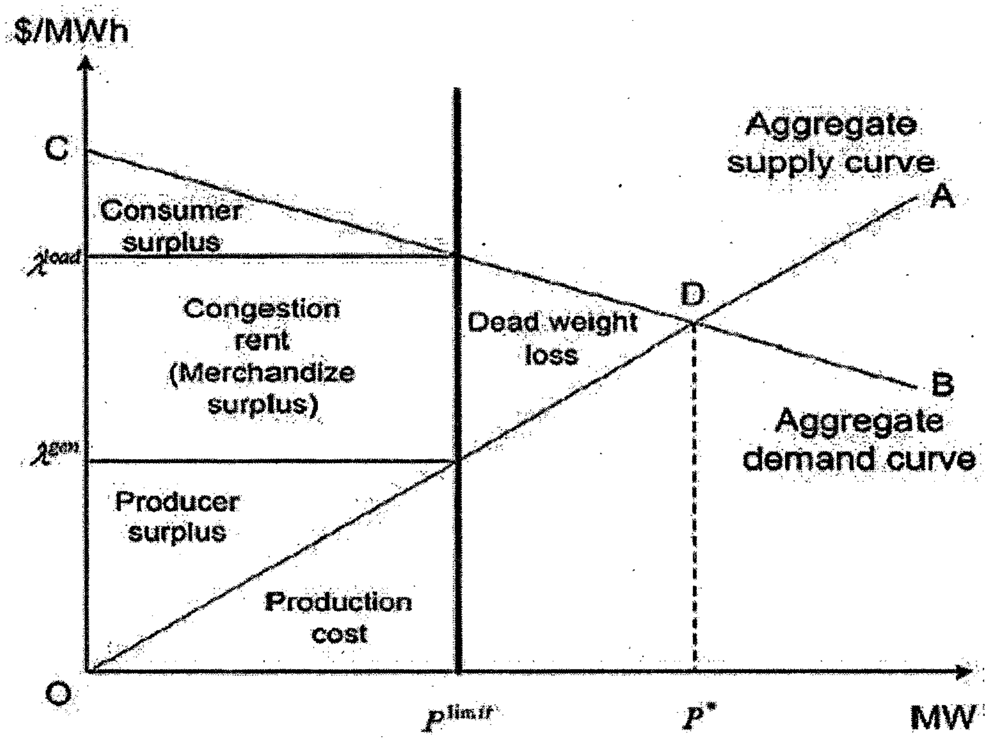


Figure 4.5: Surplus under constrained case without TCSC

balance, line limit, voltage limits and capacity limit constraints. The Lagrange operator of the equality real power balance constraints gives the nodal price of energy. The producer's surplus (PS), consumer surplus (CS) and the congestion rent or merchandize surplus (MS) can be calculated.

When TCSC is used in appropriate location with suitable size to reduce congestion, the resulting situation for the simple two-bus system is shown in Fig. 4.6. In un-congested zone, where generally generator is located, price increases. However, in congested zone, where load is located, price decreases. The congestion rent (i.e. merchandize surplus), that ISO collect from the market participants, due to LMP difference at the source and sink also decreases. This results in increase in both consumer and producer surplus. As shown in Fig.4.6 , the maximum power that can be transferred over the line without FACTS device is $P^{limit}$ and price at generator and load buses is $\lambda^{gen}$ and $\lambda^{load}$, respectively. The congestion rent collected by ISO is given by the area EGHFE, which is simply the price difference multiplied by the maximum flow through the link; $P^{limit} \times (\lambda^{load} - \lambda^{gen})$. The consumer and producer surplus are given by the triangular areas EGCE and FHOF, respectively.

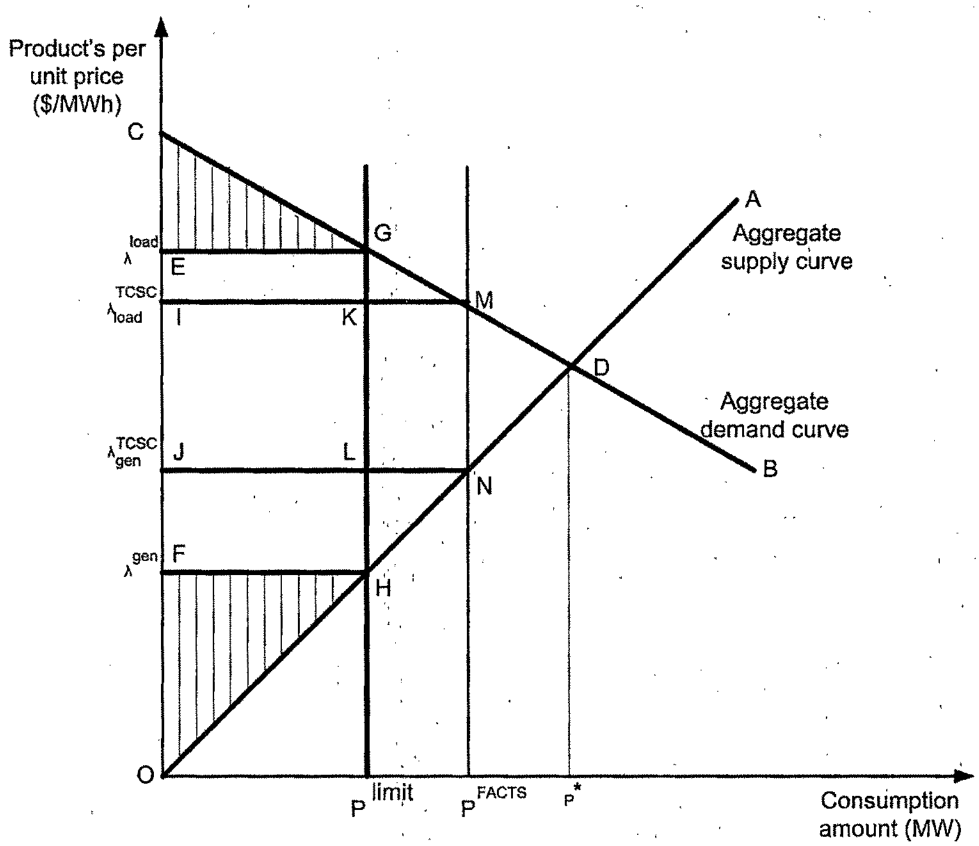


Figure 4.6: Surplus under constrained case with TCSC

With TCSC installed in the system, there is more power transfer possible over the line, as FACTS device helps to relieve congestion. It is given by $P^{TCSC}$. The prices at two locations also changes. At load side it decreases to $\lambda_{load}^{TCSC}$ and at generator side it increases to $\lambda_{gen}^{TCSC}$, so that the nodal price spread is small. The effect is that both the consumer and producer surplus increases, which are given by the areas IMCI and JNOJ, respectively. The congestion rent also changes, which is given by the area IMNJI. Before FACTS implementation, the congestion rent is given by area EGHFE, that is larger than the area IMNJI. There is a net increase in social welfare due to use of TCSC given by area GMNHG.

Lin et al. [24]used interior point method for system expansion with UPFC to maximize social welfare and to manage congestion. Yu et al. [75] used Mixed Integer Non-linear programming for optimal location of FACTS to maximize social welfare based on multiple time periods. But it ignored the impact of FACTS on reactive power flow. Verma et al.[94] used sensitivity based approach to study the impact of UPFC on real and reactive power spot prices, but they had ignored its installation cost. Literature survey reveals that no research work has been carried out in which social welfare has been maximized considering installation cost of TCSC.

So, in this chapter, Particle Swarm Optimization based algorithm has been suggested to find optimal location and setting of TCSC to maximize Social Welfare, considering its installation cost in competitive electricity market. PSO is used to simultaneously optimized active power output of generators, bus voltages of generators, TCSC reactance and its location. The performance of the proposed algorithm has been tested on IEEE 6-bus test system, IEEE 30-bus test system and practical Uttar Pradesh State Electricity Board (UP-SEB, INDIA) 75-bus test systems. Also, the obtained results are compared with those of other published paper, classical methods and Evolutionary Programming method.

## 4.2 OPF formulation and swarm initialization in PSO

The major steps involved in the OPF formulation are given below:

### 4.2.1 Initialization of a population

A particle consists of continuous and integer control variables. The continuous variables include the generators' active power outputs ($PG_2$,..... $PG_{NG}$), generators' bus voltages ($VG_1$,.....$VG_{NG}$) and reactance($X_c$) value of TCSC. Generators' active powers and generators' bus voltages are generated randomly within their permissible minimum and maximum limits. Reactance of TCSC is generated randomly between 0 and 1 (normalized form, $X_{(N)}$) and its actual value ($X_{(D)}$,Denormalized value) is found using equ. 4.4

$$X_{(D)} = X_{(min)} + (X_{max} - X_{min}) \times X_{(N)} \tag{4.4}$$

Where,

$X_{min}$ and $X_{max}$ are minimum and maximum values of the variable.

The integer variable consists of possible location (*Loc*) of a TCSC between the two buses.

The particles are generated in matrix from as shown in Table 4.1.

Table 4.1: Representation of a particle

| Particle No. | Continuous control variables | | | | | | | Integer control variables |
|---|---|---|---|---|---|---|---|---|
| | $PG_2$ | ... | $PG_{NG}$ | $VG_1$ | ... | $VG_{NG}$ | $X_c$ | Location |
| 1 | $PG_{2,1}$ | ... | $PG_{NG,1}$ | $VG_{1,1}$ | ... | $VG_{NG,1}$ | $X_{c1}$ | $Loc_1$ |
| 2 | $PG_{2,2}$ | ... | $PG_{NG,2}$ | $VG_{1,2}$ | ... | $VG_{NG,2}$ | $X_{c2}$ | $Loc_2$ |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| i | $PG_{2,i}$ | ... | $PG_{NG,i}$ | $VG_{1,i}$ | ... | $VG_{NG,i}$ | $X_{ci}$ | $Loc_i$ |

Where,

$\mathbf{PG}_{2,i}, \mathbf{PG}_{NG,i}$: From $\mathbf{2^{nd}\,to\,NG^{th}}$ generators' active output powers corresponding to $i^{th}$ particle excluding slack bus generator power.

As slack generator takes care of losses during the load flow computation, its output power has not been considered as a control variable. Slack bus is assigned number 1. So, $\mathbf{PG}_1$is not considered as a control variable.

$\mathbf{VG}_{1,i}, \mathbf{VG}_{NG,i}$: From $\mathbf{1^{st}\,to\,NG^{th}}$generators' voltage magnitudes corresponding to the $i^{th}$ particle including slack bus generator voltage.

Slack bus voltage is generally specified as input variable during load flow analysis, so it is considered as a control variable during optimization.

$\mathbf{X}_{ci}$: Reactance of a TCSC corresponding to $i^{th}$ particle.

$\mathbf{Loc}_i$: Location (line number) of a TCSC corresponding to $i^{th}$ particle.

If TCSC is not included in the transmission system, then variables $\mathbf{X_c}$ and $\mathbf{Loc}_i$are not considered.

If there are total $i$ number of particles and if each particle consists of $j$ number of control variables, then the dimension of a population becomes $i\times j$

### 4.2.2 Installation of a TCSC

After generating initial population of particles, for each particle TCSC is randomly installed in the transmission line with randomly generated reactance. Thenafter, new value of bus admittance matrix is found out.

### 4.2.3 Power flow

Run full a.c. Newton-Raphson power flow for all particles to obtain generators' active and reactive output powers, bus voltages, load angles, line flows, active and reactive power losses of transmission lines.

### 4.2.4 Optimal power flow problem formulation

An OPF (fitness function) to maximize Social Welfare (to minimize total generation cost) considering installation cost of TCSC subject to various equality and inequality constraints using PSO can be formulated as equ. 4.5.

$$Min \left\{ \sum_{m=1}^{N_G} C_{Gm}(P_{Gm}) - \sum_{n=1}^{N_D} B_{Dn}(P_{Dn}) + (IC_{TCSC}) + (PF) \right\} \tag{4.5}$$

An OPF for maximizing social welfare without considering TCSC can be formulated as equ. 4.6.

$$Min \left\{ \sum_{m=1}^{N_G} C_{Gm}(P_{Gm}) - \sum_{n=1}^{N_D} B_{Dn}(P_{Dn}) + (PF) \right\} \tag{4.6}$$

This OPF is subjected to various equality constraints (power flow balance equations)

$$\left\{ P_{Gm} - P_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|cos(\delta_m - \delta_n - \theta_{mn}) = 0 \right\}, \ For\ each\ PVbus\ except\ slackbus \tag{4.7}$$

$$\left\{ Q_{Gm} - Q_{Dm} - \sum_{n=1}^{N_b} |V_m||V_n||Y_{mn}|sin(\delta_m - \delta_n - \theta_{mn}) = 0 \right\}, \ For\ each\ PQ\ bus \tag{4.8}$$

Various inequality constraints (operating constraints)

$$P_{Gm}^{min} \leq P_{Gm} \leq P_{Gm}^{max}, \ m \in N_G \tag{4.9}$$

$$Q_{Gm}^{min} \leq Q_{Gm} \leq Q_{Gm}^{max}, \ m \in N_G \tag{4.10}$$

$$|S_l| \leq S_l^{max},\ l \in N_L \tag{4.11}$$

$$V_m^{min} \leq V_m \leq V_m^{max},\ m \in N_b \tag{4.12}$$

$$X_c^{min} \leq X_c \leq X_c^{max}\ pu \tag{4.13}$$

Where,

$C_{Gm}(P_{Gm})$: Bid function of $m^{th}$generator bus (seller bus)

$B_{Dn}(P_{Dn})$: Bid function of $n^{th}$consumer bus (buyer bus)

$IC_{TCSC}$: Optimal Installation cost of TCSC (US$)

$PF$: Penalty function

$P_{Gm}, Q_{Gm}$: Active and reactive power generation at bus $m$

$P_{Dm}$, $Q_{Dm}$: Active and reactive power demand at bus $m$

$|V_m|\angle\delta_m$: Complex voltage at bus $m$

$|Y_{mn}|\angle\theta_{mn}$: $mn^{th}$element of bus admittance matrix

$P_{Gm}^{min}$, $P_{Gm}^{max}$: Minimum and maximum active power generation limits of generator $G$ connected at bus $m$ respectively

$Q_{Gm}^{min}$, $Q_{Gm}^{max}$: Minimum and maximum reactive power generation limits of generator $G$ connected at bus $m$ respectively

$S_l^{max}$: Apparent power limit of $l^{th}$transmission line

$V_m^{min}$, $V_m^{max}$: Minimum and maximum voltage magnitude limits at bus $m$ respectively

$X_c^{min}$= -0.85$\times X_{mn}$: Lower limit of reactance of TCSC

$X_c^{max}$= 0.2$\times X_{mn}$: Upper limit of reactance of TCSC

$N_L$: Total number of transmission lines

$N_b$: Total number of buses

$N_G$: Total number of generator buses

$N_D$: Total number of load buses

The cost function of TCSC is given in Siemens database and used in Cai et al [65]. Mathematically it is written as equ. 4.14.

$$C_{TCSC} = 0.0015(S)^2 - 0.7130(S) + 153.75\ (US\$/KVAR) \tag{4.14}$$

Where, $C_{TCSC}$ is the cost of TCSC in US$/KVAR and $S$ is the operating range of the TCSC in MVAR.

$$S = |Q_1| - |Q_2|\ (MVAR) \tag{4.15}$$

Where, $Q_1$ is the reactive power flow in the line before placing TCSC in MVAR and $Q_2$ is the reactive power flow in the line after placing TCSC in MVAR.

The installation cost (US$) of TCSC is given by equ. 4.16.

$$IC_{TCSC} = C_{TCSC} \times S \times 1000 \tag{4.16}$$

Square penalty function is used to handle inequality constraints such as reactive power output of generator buses, voltage magnitude of all buses and transmission line thermal limits as shown in equs. 4.17 and 4.18.

$$PF = k_1 \times \sum_{m=1}^{N_G} f(Q_{Gm}) + k_2 \times \sum_{m=1}^{N} f(V_m) + k_3 \times \sum_{m=1}^{N_L} f(S_{lm}) \tag{4.17}$$

$$f(x) = \begin{cases} 0,\ if\ x^{min} \le x \le x^{max} \\ (x - x^{max})^2, if\ x > x^{max} \\ (x^{min} - x)^2, if\ x < x^{min} \end{cases} \tag{4.18}$$

Where,

$k_1$, $k_2$, $k_3$: Penalty coefficients for reactive output power of generator buses ($Q_{Gm}$), voltage magnitude ($V_m$) of all buses and transmission line loading ($S_{lm}$), respectively. The value of each coefficient is equal to 1000.

$x^{min}$, $x^{max}$: Minimum and maximum limits of variable $x$.

## 4.3 Social welfare of various market participants

Social welfare was originally defined by the Bergson-Samuelson social welfare function and latter on modified by the economists to refer to the benefit of various participants [1]. The benefit to the generator is the revenue minus the generation cost, referred to as the generator surplus (Producer surplus). It can be also expressed as equ. 4.19, if the spot price at the generator bus is known.

$$producer\ surplus = \sum_{m=1}^{N_G} \frac{1}{2}(\lambda_m - b_{gm}) \times (P_{Gm} - P_{Gm}^{min}) \tag{4.19}$$

Where,

$\lambda_m$ is the spot price at generator bus $m$,

$b_{gm}$ is the linear coefficient in the quadratic generator bid function,

$P_{Gm}$ is the real power output of generator $m$,

$P_{Gm}^{min}$ is minimum real power generation limit of generator $m$.

Consumer surplus is the benefit obtained to consumer from the consumption of electrical energy as given in equ. 4.20

$$consumer\ surplus = \sum_{n=1}^{N_D} \frac{1}{2}(b_{dn} - \lambda_n) \times (P_{Dn} - P_{Dn}^{min}) \tag{4.20}$$

Where,

$b_{dn}$is the linear coefficient in the quadratic demand function,

$\lambda_n$ is the spot price at load bus $n$,

$P_{Dn}$is the real power demand at load bus $n$,

$P_{Dn}^{min}$ is minimum real power demand limit at load bus $n$.

Transmission network is managed by a non-profit organization known as the Wholesaler ( Merchandize). Different spot prices exist at the generator buses and load buses due to the losses and congestion. So merchandize surplus is the revenue obtained to wholesaler to compensate losses and congestion as given in equ. 4.21

$$merchandize\ surplus = \sum_{n=1}^{N_D}(\lambda_n \times P_{Dn}) - \sum_{m=1}^{N_G}(\lambda_m \times P_{Gm}) \tag{4.21}$$

Social welfare is the addition of producer surplus, consumer surplus and merchandize surplus.

## 4.4 PSO based algorithm to optimally locate TCSC to maximize social welfare

1. Input the data of lines, generators, buses and loads. Choose population size of particles and convergence criterion. Define the type of power transaction.

2. Select generators' active power output excluding slack bus generator power, voltage magnitude of all generator buses including slack bus voltage, reactance setting of TCSC and location (line number) of TCSC as control variables. If TCSC is not included in the OPF problem, then variables namely reactance setting of TCSC and location are not considered.

3. Randomly generate population of particles in such a way that their variables fall within their feasible limits.

4. Modify the bus admittance matrix.

5. Run full a.c. Newton-Raphson load flow to get line flows, active power generations, reactive power generations, line losses and voltage magnitude of all buses.

6. Calculate the penalty function of each particle using equs. 4.17 and 4.18.

7. Calculate the fitness function of each particle using equ. 4.5 (if TCSC is included in optimization) or equ. 4.6 (if TCSC is not included in optimization).

8. Find out the "global best" particle having minimum value of fitness function in the whole population and "personal best" of all particles.

9. Generate new population using eqns. 2.1 and 2.2.

10. Go to step 4 until maximum number of iterations are completed.

11. After the optimization, the fitness value of a "$g_{best}$" particle gives minimized value of total generation cost including installation cost of TCSC. Coordinates of "$g_{best}$" particle give the optimized values of generators' active power outputs, generators' bus voltages, optimal reactance setting of TCSC and location of TCSC, respectively.

12. Surplus of various market participants could be obtained using equs. 4.19, 4.20 and 4.21.

## 4.5 Results and Discussions

To establish the effectiveness of the proposed method in maximizing Social Welfare of various market participants, the simulation studies were conducted on the following three sample test systems.

1. IEEE 6-bus test system as described in Appendix A

2. IEEE 30-bus test system as described in Appendix B

3. A practical 75-bus UP state electricity board (UPSEB) system representing 220KV and 400KV network as described in Appendix C.

In this chapter, Particle Swarm Optimization based algorithm has been suggested to find optimal location and setting of TCSC to maximize Social Welfare, considering its installation cost in competitive electricity market. PSO is used to simultaneously optimized active power output of generators, bus voltages of generators, TCSC reactance and its location. Also, the obtained results have been compared with those of other published paper, classical methods and Evolutionary Programming methods.

### 4.5.1 IEEE 6-bus test system

The data of 6 bus system [149] consists of 3 generators and 11 transmission lines. As shown in Table 4.2, generation cost minimization OPF is solved using PSO (Case 1A) and non-linear programming (MINOS solver, Case 1C) without using TCSC for 6 bus system. The obtained total generation cost is 3,128.8 \$/h by PSO, whereas it is 3,143.97 \$/h by MINOS. It is because PSO can simultaneously optimize generators' active power output and generator bus voltages. So it can find optimal solution. But MINOS could not find the optimal solution. Active power loss and reactive power losses obtained from PSO are lesser than those obtained from MINOS. Reactive power output of generators no. 2 and 3 are reduced by PSO, so they can be even more efficiently utilized. In case 1B, optimal reactance setting and location of TCSC are found by PSO to minimize the composite objective function which consists of total generation cost and installation cost of TCSC. Total generation cost is 3,125.3 \$/h, which is lesser than those obtained in cases 1A and 1C. Optimal installation cost of TCSC obtained is $0.3977\times10^6$ US \$. Optimal reactance of TCSC is negative means it operates in capacitive mode. Optimal location of TCSC is the line that is connected between bus 1 and bus 4. Also, Optimally placed TCSC significantly reduced active power losses and reactive power losses.

Table 4.2: Comparison of results of cost minimization by PSO and Non-linear programming method in IEEE 6-bus test system

| | PSO | | Non-linear programming (MINOS) in MATPOWER |
|---|---|---|---|
| | Without TCSC, (Case 1A) | With TCSC, (Case 1B) | Without TCSC, (Case 1C) |
| Total generation cost ($/h) | 3,128.8 | 3,125.3 | 3,143.97 |
| Real power output of generator 1, $(P_{G1})$MW | 52.96 | 49.98 | 77.22 |
| $P_{G2}$ | 86.28 | 89.02 | 69.27 |
| $P_{G3}$ | 77.58 | 77.62 | 70.42 |
| Total generation (MW) | 216.83 | 216.61 | 216.91 |
| Generator bus voltage, $V_1$p.u. | 1.0546 | 1.042 | 1.050 |
| $V_2$ | 1.0351 | 1.048 | 1.050 |
| $V_3$ | 1.0508 | 1.048 | 1.070 |
| TCSC setting (pu) | ... | -0.0980 | ... |
| TCSC location | ... | Between bus 1-4 | ... |
| Optimal installation cost of a TCSC (US$) | ... | $0.3977\times10^6$ | ... |
| Total active power losses (MW) | 6.826 | 6.611 | 6.908 |
| Total reactive power losses (MVAR) | 21.15 | 18.53 | 21.21 |
| Reactive power output of generator 1, $(Q_{G1})$MVAR | 58.06 | 43.36 | 25.72 |
| $Q_{G2}$ | 43.05 | 68.84 | 64.65 |
| $Q_{G3}$ | 77.11 | 63.02 | 86.64 |

Also, optimally placed TCSC by PSO improves the voltage profile at load buses, which is depicted from the Fig. 4.7.

As shown in Table 4.3 and Fig. 4.8, producers surplus, consumers surplus and merchandize surplus can be obtained using equs. 4.19, 4.20 and 4.21 respectively. Optimally placed TCSC (Case 2B) can significantly increase Consumer surplus and Producer surplus, which is the main aim of deregulation. Merchandize surplus includes cost of losses and cost of congestion. As TCSC reduces losses of the transmission system and thus removes congestion, it drastically decreases Merchandize surplus.

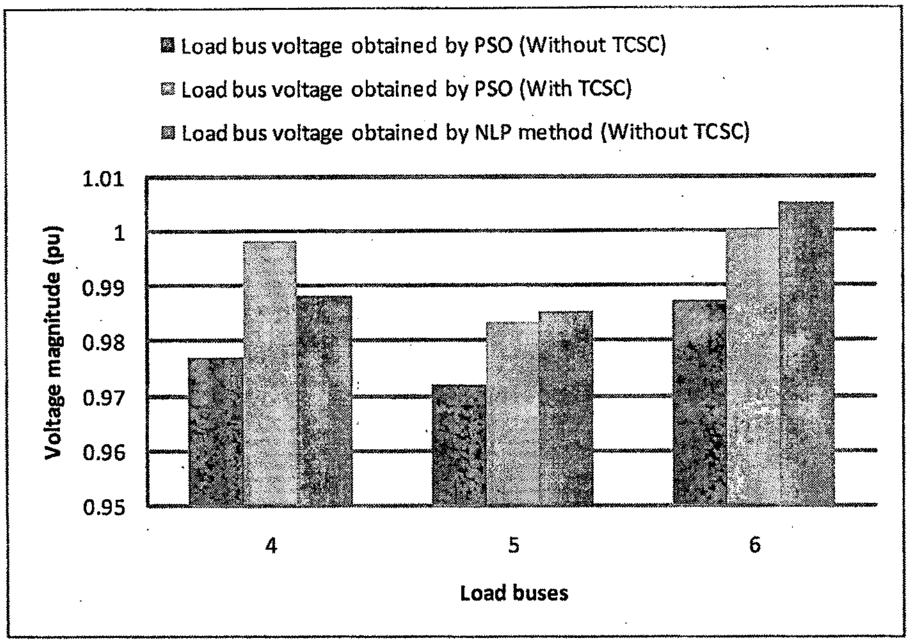


Figure 4.7: Voltage magnitude at load buses by PSO and NLP methods

Table 4.3: Comparison of surplus obtained by PSO and NLP methods

| Surplus ($/h) | PSO | | NLP |
|---|---|---|---|
| | Without TCSC (Case 2A) | With TCSC (Case 2B) | Without TCSC (Case 2C) |
| producer surplus | 56.97 | 59.653 | 44.031 |
| consumer surplus | 2,971.24 | 3,001.74 | 2,876.47 |
| merchandize surplus | 65.94 | 14.079 | 255.22 |

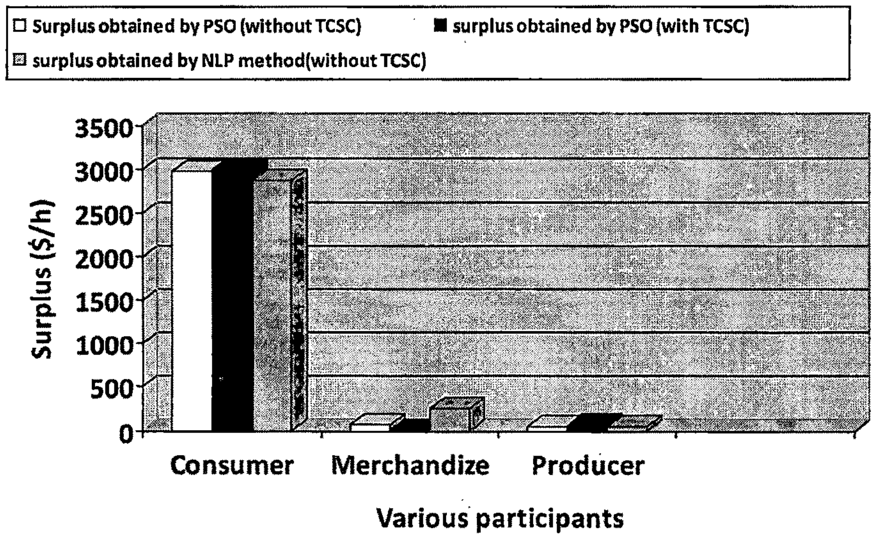


Figure 4.8: Graphical representation of comparison of surplus obtained by PSO and NLP methods

#### 4.5.1.1 Effect of PSO parameters on convergence

As PSO is a kind of stochastic optimization method, its convergence is greatly affected by the chosen parameters. So, parameters such as Cognitive parameter ($C_1$), Social parameter ($C_2$), Constriction factor ($\chi$),Maximum inertia weight ($W_{max}$), Minimum inertia weight ($W_{min}$), upper limit of velocity ($V_{max}$), and lower limit of velocity ($V_{min}$or -$V_{max}$) were selected through experiments and their effect on the value of optimal generation cost had been studied. The results are shown in Table 4.4. The population of 35 particles was considered for all cases and 50 independent trials were carried out for each case. It is seen that case 3 ($C_1$=1.2, $C_2$=1, $\chi$=0.3, $W_{max}$=0.7, $W_{min}$=0.3, $V_{max}$=0.25, and -$V_{max}$=-0.25) gave the minimum (best) generation cost of 3,125.3 US$/h. Convergence criterion was 25 iterations. The variation in generation cost with the iteration number is shown in Fig. 4.9 for NLP method and in Fig. 4.10 for PSO method respectively. Comparing both the figures, it is observed that PSO provides global solution in less than 15 iterations, whereas NLP could not find the global solution.

Table 4.4: Effect of PSO parameters on convergence

| case | $C_1$,$C_2$ | $\chi$ | $W_{max}$,$W_{min}$ | $V_{max}$,-$V_{max}$ | Best generation cost ($/h) |
|---|---|---|---|---|---|
| 1 | 1, 1.3 | 0.6 | 1, 0.5 | 0.35, -0.35 | 3,125.5 |
| 2 | 1.1, 2 | 0.4 | 0.8, 0.4 | 0.30, -0.30 | 3,127.7 |
| 3 | 1.2, 1 | 0.3 | 0.7, 0.3 | 0.25, -0.25 | 3,125.3 |
| 4 | 2, 1.6 | 0.2 | 0.75, 0.35 | 0.20, -0.20 | 3,128.2 |
| 5 | 2, 2 | 0.1 | 0.9, 0.4 | 0.10, -0.10 | 3,126.1 |
| Population size | | | | | 35 particles |
| Convergence criterion | | | | | 25 iterations |

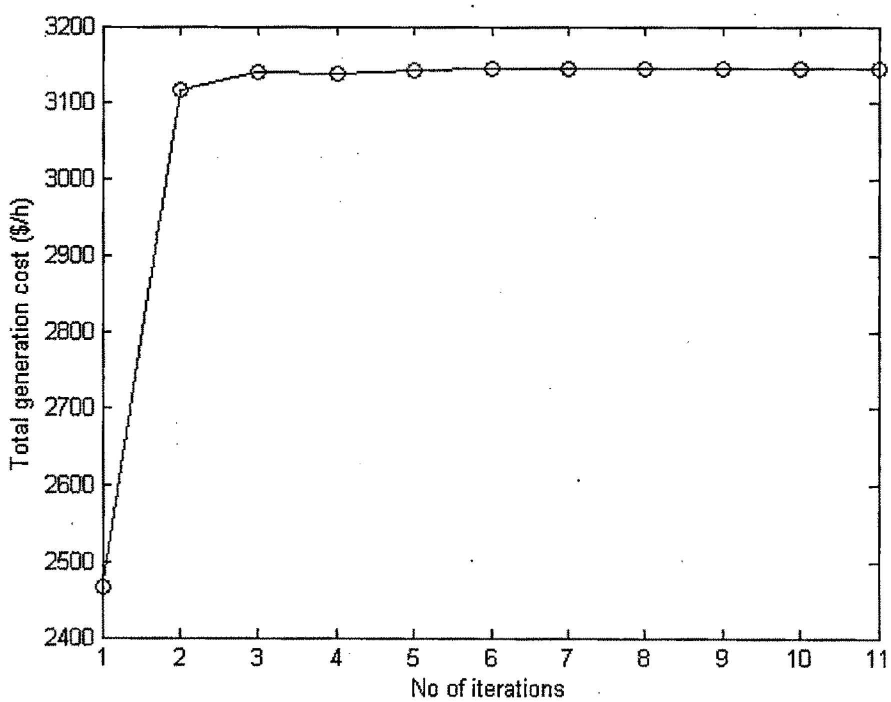


Figure 4.9: Convergence characteristic of NLP method

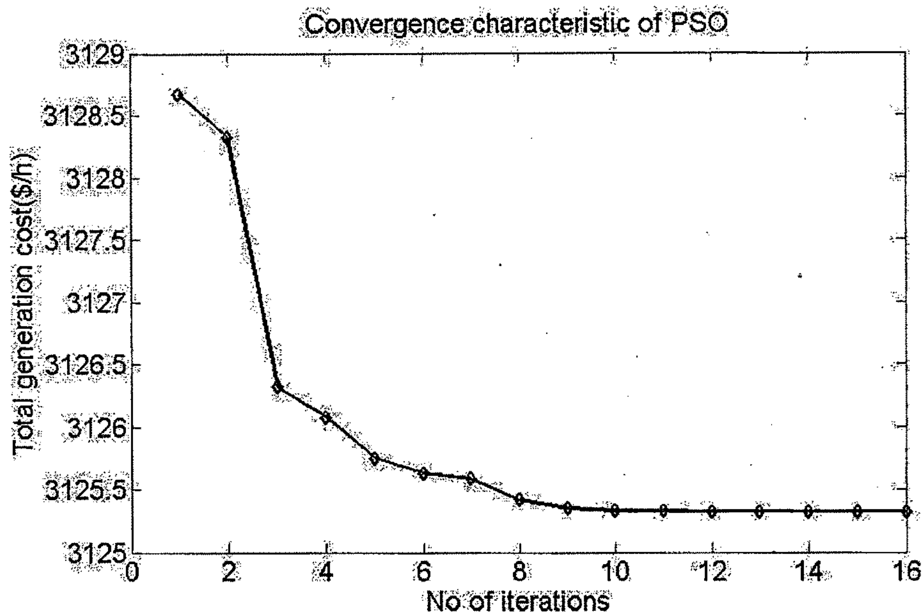


Figure 4.10: Convergence characteristic of PSO method

### 4.5.2 IEEE 30-bus test system

The data of 30 bus system [105] consists of 6 generator buses, 24 load buses and 41 transmission lines. Total two capacitors at buses 5 and 24 are connected to fulfill reactive power demand of the loads. As shown in Table 4.5, generation cost minimization OPF was solved using PSO in Case 3A. Case 3C shows the results reported in [88], in which the OPF was solved by Evolutionary Programming method. Comparing the Case 3A and Case 3C, it is concluded that PSO gives much better results than EP method. It is because PSO can simultaneously optimize generators' active power output and generators' bus voltages. Whereas, in Case 3C, only generators' active powers were optimized. PSO also requires lesser iterations than EP method in obtaining global solution. Losses obtained by the proposed method are lesser than those obtained by EP method.

Fig. 4.11shows the voltage magnitude of various load buses before placing TCSC and after placing TCSC. Optimally placed TCSC shifted voltages of many load buses (e.g load bus 3,4,5,7 etc.) towards 1.00 pu value. Whereas for other load buses, it slightly decreased the value of bus voltages. So, it is concluded that TCSC could maintain voltage profile of the load buses at an acceptable level.

Fig. 4.12 shows the obtained consumer surplus from PSO and Evolutionary Programming

Table 4.5: Comparison of results of cost minimization by PSO and Evolutionary Programming (EP) method of IEEE 30-bus test system

| | PSO | | Results reported in [88](EP method) |
|---|---|---|---|
| | Without TCSC (Case 3A) | With TCSC (Case 3B) | Without TCSC (Case 3C) |
| Total generation cost ($/h) | 705.64 | 704.21 | 802.56 |
| Real power output of generator 1, ($P_{G1}$)MW | 144.91 | 153.07 | 176.66 |
| $P_{G2}$ | 45.93 | 35.45 | 48.73 |
| $P_{G5}$ | 17.05 | 25.49 | 21.49 |
| $P_{G8}$ | 21.94 | 18.51 | 21.90 |
| $P_{G11}$ | 13.10 | 11.74 | 12.18 |
| $P_{G13}$ | 18.91 | 17.05 | 12.00 |
| Total generation (MW) | 261.84 | 261.31 | 292.96 |
| Generator bus voltage, $V_1$p.u. | 1.017 | 1.0430 | Not reported |
| $V_2$ | 1.007 | 1.0182 | |
| $V_5$ | 1.001 | 0.9933 | |
| $V_8$ | 0.988 | 1.0140 | |
| $V_{11}$ | 1.025 | 1.0188 | |
| $V_{13}$ | 1.034 | 1.0107 | |
| TCSC setting (pu) | ... | -0.0807 | ... |
| TCSC location | ... | Line 34 (bus 25-26) | Not reported |
| Optimal installation cost of a TCSC (US$) | ... | $0.4662\times10^6$ | ... |
| Total active power losses (MW) | 8.437 | 7.905 | 9.561 |
| Total reactive power losses (MVAR) | 36.50 | 34.10 | Not reported |
| Iteration required | 15 | 15 | 40 |

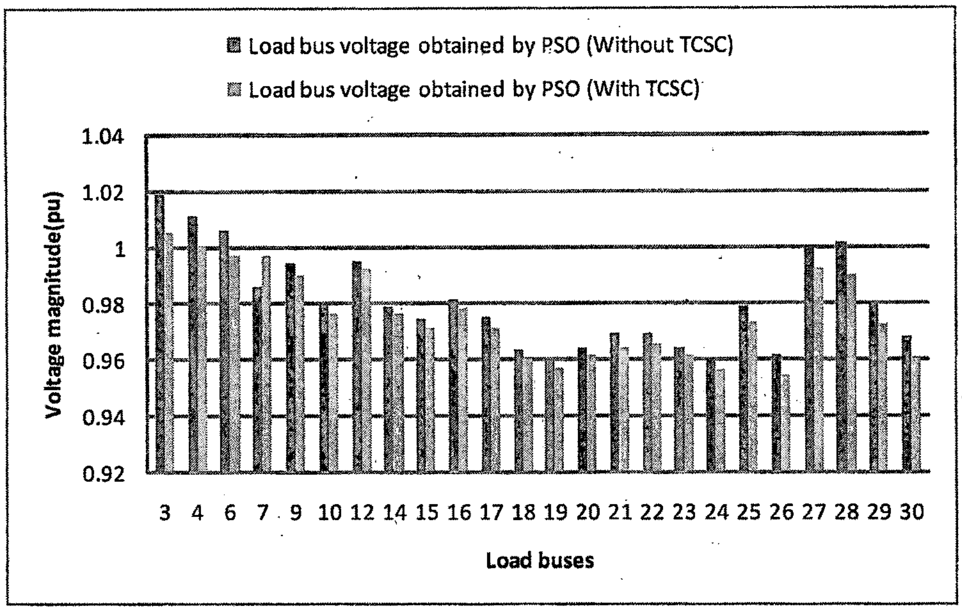


Figure 4.11: Voltage magnitude of various load buses without and with TCSC

methods. Results show that PSO outperforms EP method and optimally placed TCSC by PSO enhances consumer surplus.

Fig. 4.13 shows merchandize surplus obtained by PSO and EP methods. As optimally placed TCSC reduces active and reactive power losses, it reduces merchandize surplus.

Fig. 4.14 shows producer surplus obtained by PSO and EP methods. Optimally placed TCSC increases producer surplus by decreasing total generation cost. As producer surplus is increased, the GENCOs can obtain more revenue from selling of the electricity.

The population of 50 particles was taken for 30 bus test system. Convergence criterion taken was 40 iterations. Remaining parameters were same as that of 6 bus system. The variation in generation cost with the iteration number is shown in Fig. 4.16 for both methods. From that figure, it is depicted that PSO outperforms EP method in obtaining global solution.

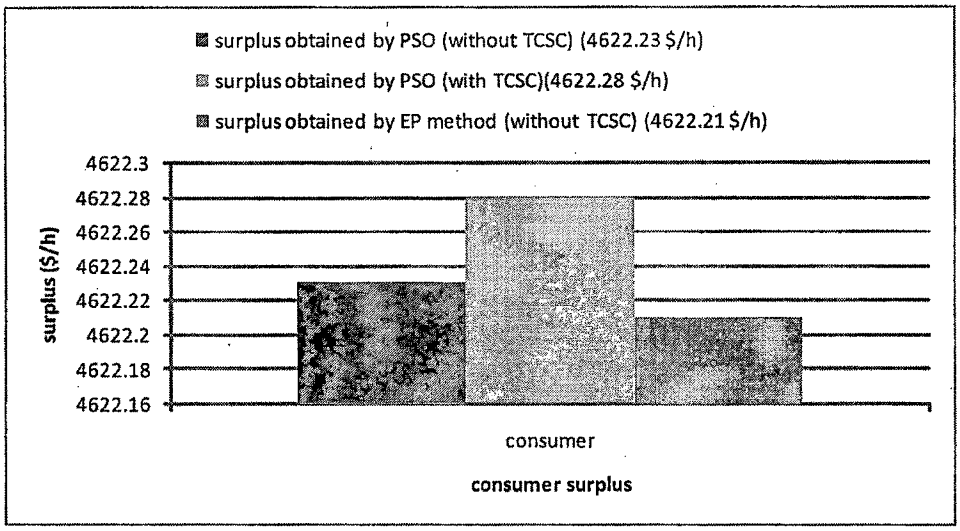


Figure 4.12: Comparison of consumer surplus obtained by PSO and EP methods

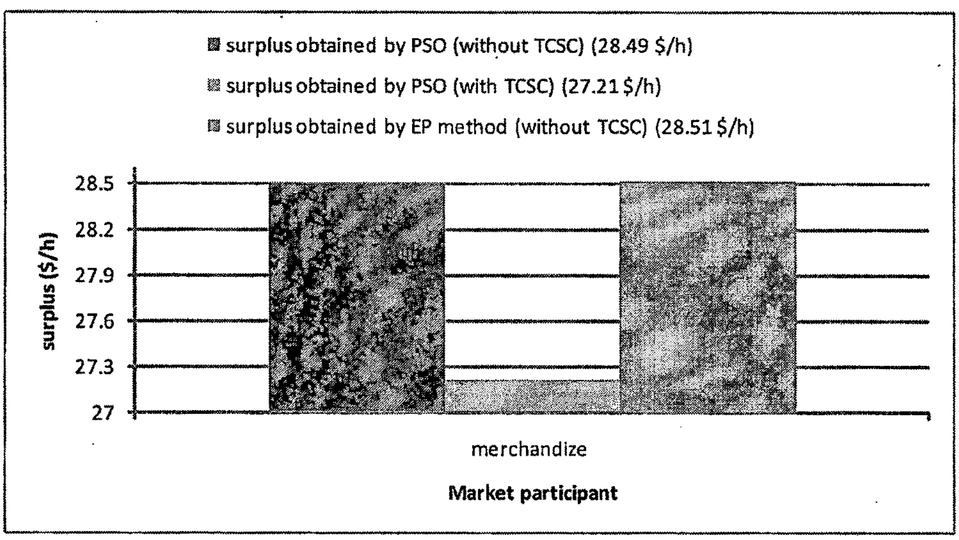


Figure 4.13: Comparison of merchandize surplus obtained by PSO and EP methods

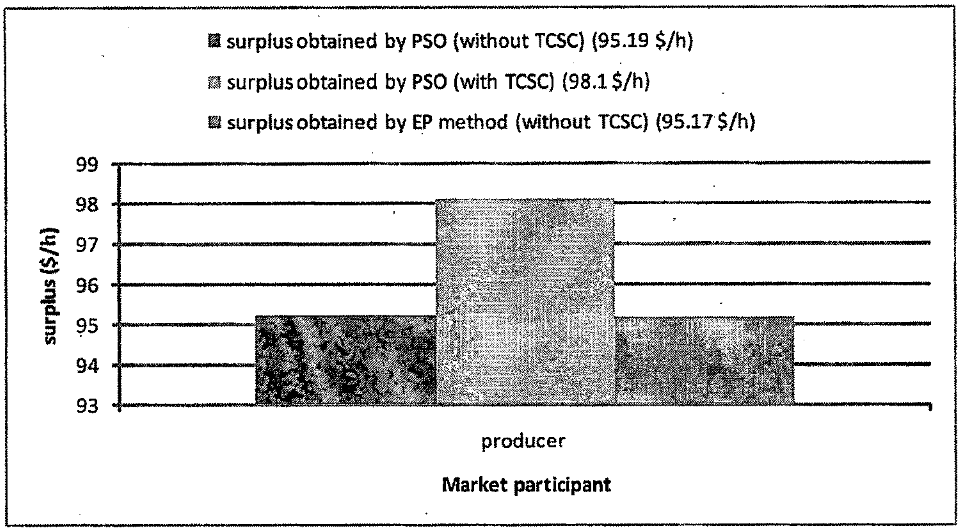


Figure 4.14: Comparison of producer surplus obtained by PSO and EP methods

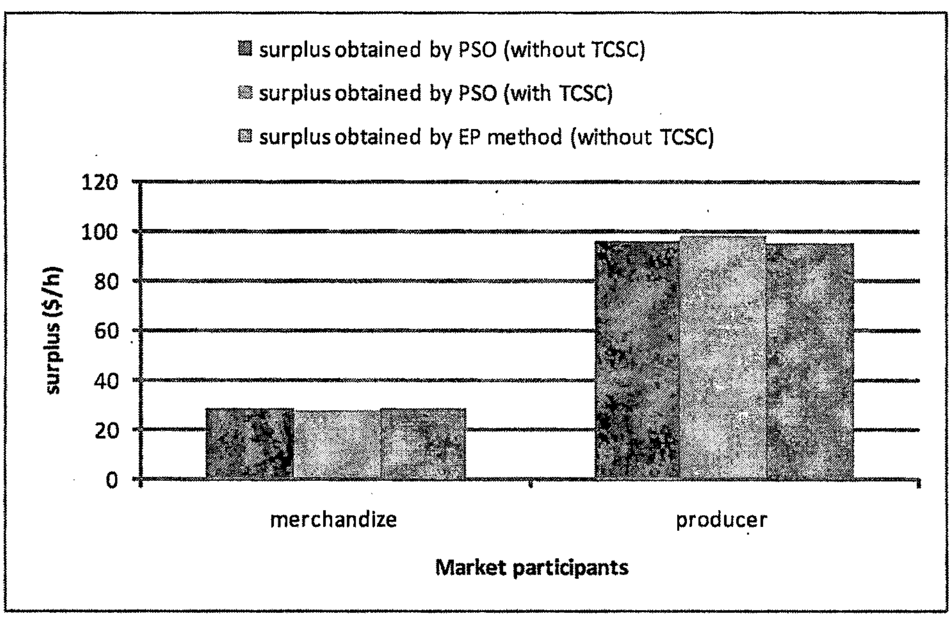


Figure 4.15: Comparison of merchandize and producer surplus obtained by PSO and EP methods

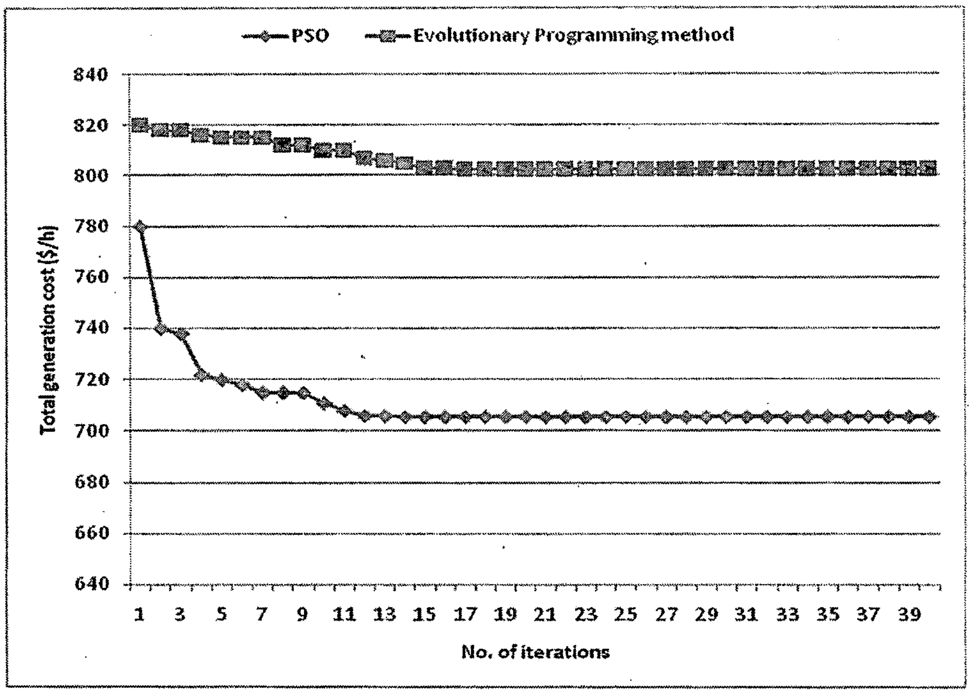


Figure 4.16: Convergence characteristic of PSO and EP in IEEE 30 bus test system

### 4.5.3 UPSEB 75-bus test system

This system consists of 15 generator buses, 60 load buses and 95 transmission lines. As shown in Table 4.6 generation cost minimization OPF was performed by PSO to obtained social benefit of various market participants. It can be seen that optimally placed TCSC decreased total generation cost to a large extent because it decreases transmission line losses. So power generation required for fulfilling the load demand decreased. Optimal setting of TCSC obtained was -0.0111 pu. i.e it operated in capacitive mode. So it had reduced effective reactance of the line 13 (bus 28-4). Optimal location of TCSC obtained was line 13 (bus 28-4). Optimal installation cost of TCSC 0btained was $1.2752 \times 10^6$US$. The total transmission losses were 202.02 MW without placing TCSC but they decreased to 194.94 MW after placing TCSC.

Table 4.6: Generation cost minimization by PSO

| | Without TCSC | With TCSC |
|---|---|---|
| Total generation cost ($/h) | $1.6066\times10^6$ | $1.5370\times10^6$ |
| Real power output of generator1, ($P_{G1}$) MW | 1015.10 | 737.18 |
| ($P_{G2}$) | 172.67 | 169.45 |
| ($P_{G3}$) | 162.48 | 168.88 |
| ($P_{G4}$) | 77.35 | 99.52 |
| ($P_{G5}$) | 352.62 | 144.74 |
| ($P_{G6}$) | 139.92 | 427.40 |
| ($P_{G7}$) | 158.01 | 24.01 |
| ($P_{G8}$) | 29.50 | 88.12 |
| ($P_{G9}$) | 384.14 | 538.91 |
| ($P_{G10}$) | 61.08 | 84.15 |
| ($P_{G11}$) | 158.30 | 180.33 |
| ($P_{G12}$) | 1800.18 | 1800.15 |
| ($P_{G13}$) | 900.15 | 900.15 |
| ($P_{G14}$) | 150.18 | 150.16 |
| ($P_{G15}$) | 238.47 | 179.92 |
| Total generation (MW) | 5800.15 | 5793.06 |
| Generator bus voltage, $V_1$p.u. | 1.041 | 1.048 |
| $V_2$ | 1.067 | 1.063 |
| $V_3$ | 1.037 | 1.001 |
| $V_4$ | 1.058 | 0.974 |
| $V_5$ | 1.022 | 1.044 |
| $V_6$ | 1.047 | 1.013 |
| $V_7$ | 1.023 | 0.986 |
| $V_8$ | 1.074 | 1.062 |
| $V_9$ | 1.049 | 1.059 |
| $V_{10}$ | 1.068 | 1.060 |
| $V_{11}$ | 1.027 | 1.043 |
| $V_{12}$ | 1.017 | 1.018 |
| $V_{13}$ | 0.995 | 0.994 |
| $V_{14}$ | 0.999 | 1.042 |
| $V_{15}$ | 1.013 | 1.018 |
| TCSC setting (pu) | — | -0.0111 |
| TCSC location | — | Line 13 (bus 28-4) |
| Optimal installation cost of a TCSC (US$) | — | $1.2752\times10^6$ |
| Total active power losses (MW) | 202.02 | 194.94 |
| No. of iterations required | 30 | 30 |

Table 4.7 and Fig. 4.17 show the surplus obtained by various market participants. It can be seen that consumer and producer surplus were increased after placing TCSC. It decreased merchandize surplus. Merchandize surplus included cost of losses and cost of congestion. As TCSC reduced losses of the transmission system, it drastically decreased Merchandize surplus.

Table 4.7: Surplus of various market participants

| Surplus ($/h) | Without TCSC | With TCSC |
|---|---|---|
| Consumer surplus | 3,293 | 3,365 |
| Merchandize surplus | 95 | 82 |
| Producer surplus | 584 | 695 |

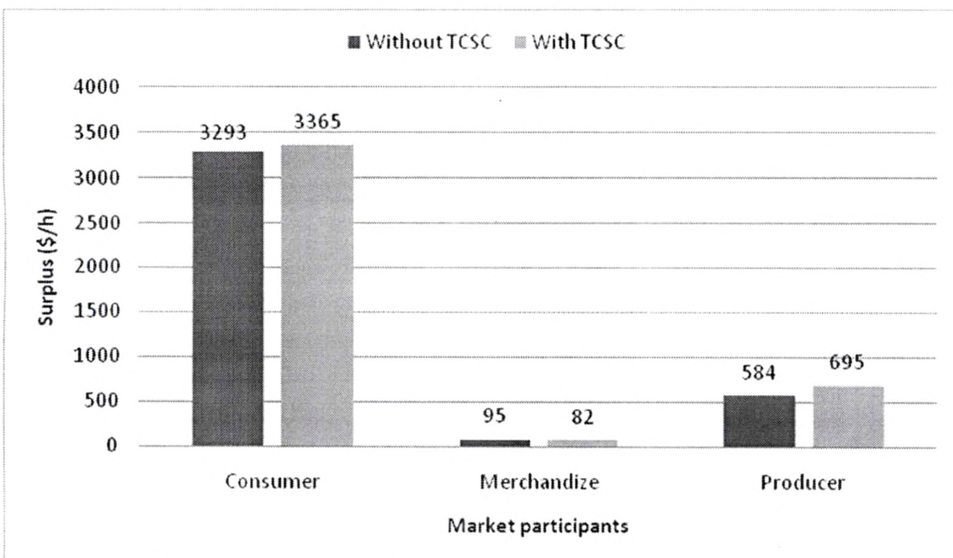


Figure 4.17: Surplus of various market participants

Fig. 4.18 shows the effect of TCSC on the voltage profile of some heavily loaded load buses. It can be clearly seen that voltage profile of the mentioned load buses became smooth after placing TCSC. Thus, it improved voltage stability of the system.

Table 4.8: Selected parameters of PSO

| No. of particles | No. of iterations | $C_1$,$C_2$ | $\chi$ | $W_{max}$,$W_{min}$ | $V_{max}$,-$V_{max}$ | Generation cost ($/h) |
|---|---|---|---|---|---|---|
| 100 | 35 | 1.2, 1 | 0.3 | 0.7, 0.3 | 0.25, -0.25 | $1.5370\times10^6$ |

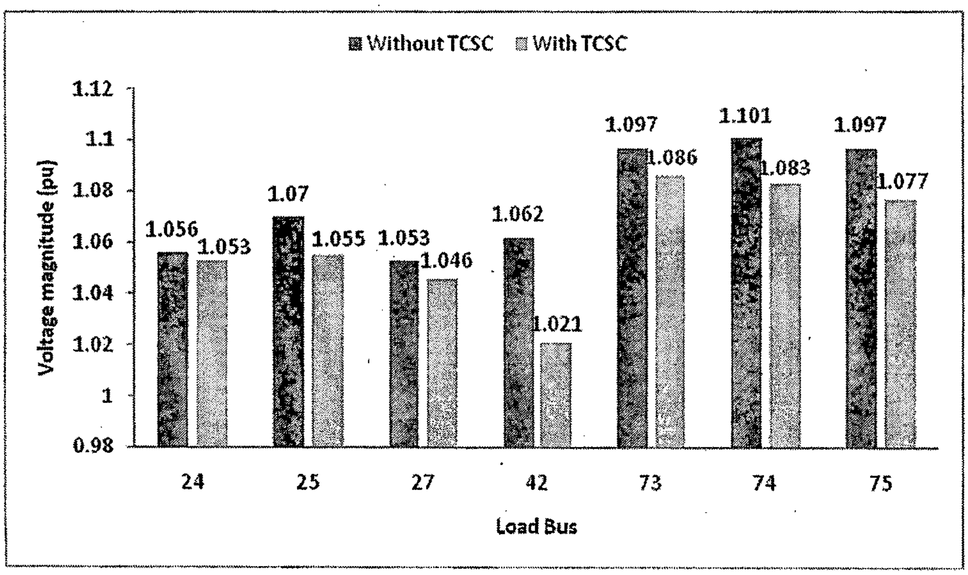


Figure 4.18: Effect of TCSC on voltage profile of some heavily loaded load buses

Table 4.8 shows selected parameter of PSO.

Fig. 4.19 shows convergence characteristic of PSO. It is seen that fitness of the best particle gradually decreased and finally it obtained its minimum (optimum) value. It converges in within 30 iterations which indicates that it is a fast method and can easily obtain a global solution.

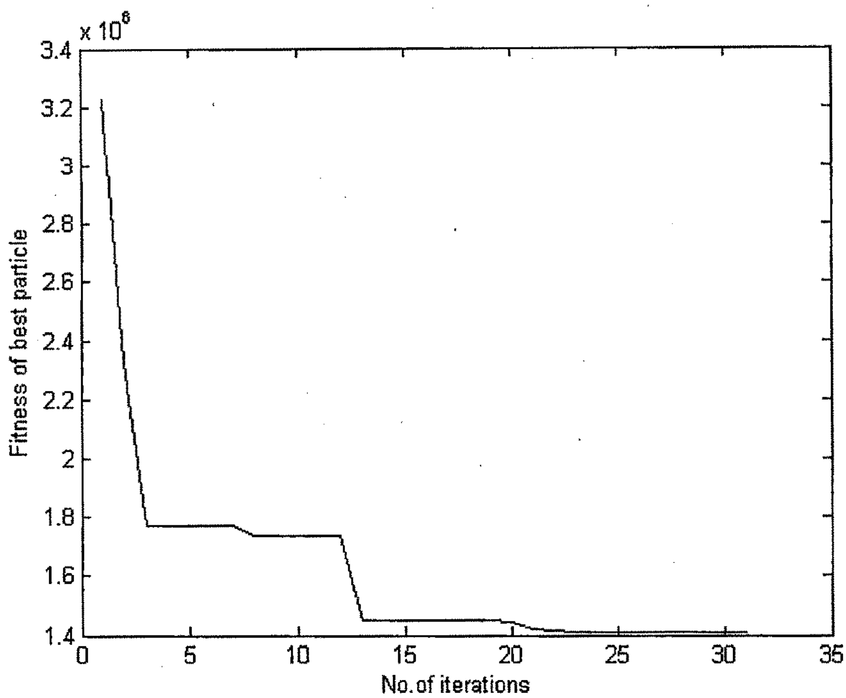


Figure 4.19: Convergence characteristic of PSO

## 4.6 Conclusions

This chapter has suggested PSO based algorithm to find the best location and setting of TCSC to maximize social welfare, minimize total generation cost and installation cost of TCSC while satisfying various constraints. The contribution of this chapter to the available literature can be summarized as follows:

1. Different simulation results discussed above show a remarkable rise in social welfare of various market participants and decrease in total generation cost.

2. Optimally placed TCSC improves voltage profile of various load buses. Thus, it improves voltage stability of the power system.

3. PSO based algorithm outperformed Non-linear programming method (NLP) and Evolutionary Programming (EP) methods in terms of quality of solution.