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# An Efficient Approach for Optimal Placement of TCSC in Double Auction Power Market

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***Abstract*—**This paper proposes an investment cost recovery based efficient and fast sequential optimization approach to optimal allocation of thyristor controlled series compensator (TCSC) in competitive power market. The optimization technique has been used with an objective to maximizing the social welfare and minimizing the device installation cost by suitable location and rating of TCSC in the system. The effectiveness of proposed approach for location of TCSC has been compared with some existing methods of TCSC placement, in terms of its impact on social welfare, TCSC investment recovery and optimal generation as well as load patterns. The results have been obtained on modified IEEE 14-bus system.

***Keywords*—**Double auction market, Investment cost recovery, Optimal location, Social welfare, TCSC

## I. Introduction

THE experience of last twenty years tells that electricity companies can be divided into those parts which are still natural monopolies and those parts where it is possible to have competition and to create a market for electricity. This experience is now being used all over the world to create cheaper electricity by means of competition amongst power stations and amongst companies that are in the business of purchasing and reselling electricity.

With the increased power demand, more interconnections with limited transmission expansion and enhanced trading activities in the electricity market it has been challenging task to operate the system in an efficient manner. Flexible ac transmission systems (FACTS) are considered to be one technology that can benefit the emerging power system in terms of enhancing the system stability, providing better voltage control and increased loading capability of existing transmission systems with possibility to load lines much closer to their thermal limits [1], [2].

Recently, there has been growing interest in allocation of FACTS devices for achieving different objectives for transmission network. Gerbex et al. [3] have used a genetic algorithm to seek the optimal location of FACTS devices in a power system. Optimizations have been performed on the location of the device as well as their values. However, in [3] the number of devices to be installed is decided arbitrarily not by optimization. The impact of TCSC on congestion and spot pricing is presented in [4]. The paper demonstrated that the TCSC could reduce congestion as well as the losses.

References [5] and [6] have proposed optimal allocation methods for TCSC to eliminate the line overloads, where sensitivity index is introduced for ranking the optimal placement. Priority list method for TCSC allocation for congestion management has been proposed in [7].

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However all of these works [3-7] have not taken into account the cost of installation and maintenance of FACTS devices.

Reference [8] proposes an approach for optimal location of FACTS devices and evaluating its impact on annual total cost, device investment cost and benefit due to device installation. Song et al. [9] suggested the proper location of each device to enhance the steady state security. In [10], application of different FACTS devices has been presented to control the power flow in the power system. Recently some other optimization techniques based on various artificial intelligence techniques like evolutionary programming (EP) [11], particle swarm optimization (PSO), hybrid particle swarm optimization (HPSO) etc. have also been developed for the analysis of deregulated power sector. However, these techniques take much more time to simulate the problem and sometimes do not converge to a single optimal value and provide approximate solutions.

Review of works from the literature revels that the optimal FACTS solution problem is one of the main points for the enhancement of transmission systems, and recently it has received great attention from power system researchers. However, to the best of author's knowledge, no attempt has been made to suggest a simple, fast, reliable and efficient method for determining the optimal location, rating, cost of FACTS controllers, social welfare and investment cost recovery of FACTS devices simultaneously in the deregulated power sector.

This paper proposes an efficient, reliable and fast optimization approach to optimally locate the TCSC in the deregulated power sector. The proposed approach is based on investment recovery of FACTS devices with sequential variation in control parameters of the device. MATLAB programming codes for the proposed technique is developed and incorporated for the simulation purpose. MATPOWER [12] is a package of MATLAB m-files for solving power flow and optimal power flow problems. It is intended as a simulation tool for researchers and educators which will be easy to use and modify. In this paper, the MATPOWER m-files are changed with adding the proposed sequential optimization codes to solve the problem. Results are determined for all possible locations, degree of compensation, reactance of TCSC, maximization of social welfare and recovery of investment cost of TCSC in the networks. The double auction bidding model is used in which gencos as well as demands both are allowed to offers and bids their prices to independent system operator (ISO). The amount to be paid by each demand and amount to be received by each genco is determined by most probable bidding price approach, after optimal location of TCSC in the network.

## II. Mathematical Formulation

In the considered power market model, bulk loads as well as retailers are required to bid their maximum demand and price

function. All generators are also required to bid their generation cost function along with their maximum generation.

*A. TCSC Modeling*

The TCSC can serve as the capacitive or inductive compensation respectively by directly modifying the reactance of the transmission line. In this paper, the model of the TCSC is developed to be suitable for steady-state. It is modeled as variable reactance connected in series with transmission line. The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Fig. 1.

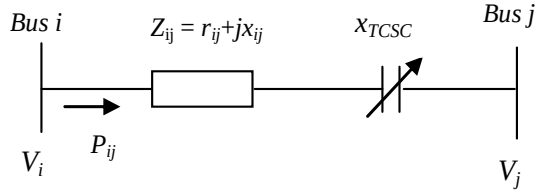


Fig. 1 Model of transmission line with TCSC

The rated value of TCSC is a function of the reactance of the transmission line where the TCSC is installed:

$$x_{line} = x_{ij} + x_{TCSC} \quad (1)$$

where $x_{TCSC} = k_{TCSC}. x_{line}$

$x_{line}$ is the overall line reactance between bus-*i* and *j* with TCSC installation. $x_{TCSC}$ is the reactance of TCSC and $k_{TCSC}$ is the coefficient which represents the compensation level of TCSC ( $-0.7 \le k_{TCSC} \le 0.2$ ). The working range of reactance of TCSC is fixed between *-0.7* $x_{line}$ and *0.2* $x_{line}$ [3], [13].

*B. Investment Cost*

According to wibowo et al. [8] investment cost of TCSC is given by:

$$C_{TCSC} = 0.0015.S_{TCSC}^2 - 0.7130.S_{TCSC} + 153.75 \quad \$/\text{kVar} \quad (2)$$

where $C_{TCSC}$ is the cost of TCSC in US$/kVar and $S_{TCSC}$ is the operating range of TCSC in MVar. Overall investment cost $IC_{TCSC}$ ($/hr) is calculated as follows:

$$IC_{TCSC} = \left( \frac{C_{TCSC} \times S_{TCSC} \times 1000}{8760} \right) \ \$/\text{hr} \quad (3)$$

Due to high cost of FACTS devices it is necessary to use cost-benefit analysis to analyze whether a new FACTS device is cost effective amongst several candidate locations when actually installed. In this respect, the following expression is used to convert the investment cost into annual term [8]:

$$AIC_{TCSC} = IC_{TCSC} \frac{ir(1+ir)^{LT}}{(1+ir)^{LT} - 1} \quad (4)$$

where $AIC_{TCSC}$ is the annual TCSC investment cost, *ir* is the interest rate and *LT* is the life time of device. In this work, it is assumed that the interest rate *ir* = 0.05, *LT* = 10 years.

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*C. Power Pool*

The gencos participating in the pool offer their cost function and maximum generation, which they want to deliver to the pool. Similarly loads bid their price function as well as their maximum demand, which they are willing to take from the pool [14]. After optimization of social welfare the demand as well generation at all the buses are known.
Let

$$Pd^p = \{Pd_j^p ; j=1,2,3,....,nd\} \quad (5)$$

be the vector of pool real power demand and

$$Pg^p = \{Pg_i^p ; i=1,2,3,....,ng\} \quad (6)$$

be the vector of pool real power generation.
Let the vector of the total real power demand and generation is:

$$Pd^T = \{Pd_j^T ; j=1,2,3,....,nd\} \quad (7)$$

$$Pg^T = \{Pg_i^T ; i=1,2,3,....,ng\} \quad (8)$$

*D. Objective Function and Constraints*

Consider a system having total *nb* number of buses, *ng* number of generators and *nd* number of loads. Let the generation cost curve offer to the pool by generator at bus *i* be denoted by $C_i(Pg_i^p)$ and the worth function (which is also called benefit curve [15]) for load that is price dependent be $B_j(Pd_j^p)$. It represents the price the load is willing to pay to purchase an amount of power $Pd_j^p$.

Mathematically, the objective function is to maximize the social welfare and minimize the investment cost of TCSCs. So the objective function is given as:

$$F_{obj} = max\left\{ \sum_{j=1}^{nd} B_j(Pd_j^p) - \sum_{i=1}^{ng} C_i(Pg_i^p) - \sum_{k=1}^{N} IC_{TCSC}(k) \right\} \ \$/h \quad (9)$$

subject to the following transmission network constraints and FACTS device constraints:

- Power balance equations (equality constraints)

$$\left.\begin{aligned} P_i(V,\varphi) - P_i^{net} &= 0 \ \} \text{for each PQ bus i} \\ Q_i(V,\varphi) - Q_i^{net} &= 0 \ \} \text{for each PQ bus i} \\ P_m(V,\varphi) - P_m^{net} &= 0 \ \} \text{for each PV bus m} \end{aligned}\right\} \quad (10)$$

- The inequality constraints

$$\left.\begin{aligned} &Pg_i^{min} \le Pg_i \le Pg_i^{max}, Qg_i^{min} \le Qg_i \le Qg_i^{max}, \\ &V_i^{min} \le V_i \le V_i^{max}, \phi_i^{min} \le \phi_i \le \phi_i^{max}, \\ &MVAf_{ij} \le MVAf_{ij}^{max}, -0.7x_{ij} \le x_{TCSC} \le 0.2x_{ij} \end{aligned}\right\} ; \text{i and j} \forall \text{nb} \quad (11)$$

where

| | |
|---|---|
| $N$ | number of TCSC |
| $P_i$ , $Q_i$ | calculated real and reactive powers for PQ bus i; |
| $P_i^{net}$ , $Q_i^{net}$ | specified real and reactive powers for PQ bus i; |
| $P_m$ , $P_m^{net}$ | calculated and specified real power for PV bus m; |
| $V_i$, $\phi_i$ | voltage magnitude and phase angle at bus i; |
| $Pg_i^{min}$ , $Pg_i^{max}$ | real power generation limits at bus i; |
| $Qg_i^{min}$ , $Qg_i^{max}$ | reactive power generation limits at bus i; |
| $MVAf_{ij}^{max}$ | maximum apparent power flow limit of transmission line connecting bus i and bus j; |
| $x_{TCSC}$, $x_{ij}$ | reactance added to the line by placing TCSC and reactance of the line connecting bus i and bus j. |

With the offer characteristics of all pool generators and bidding characteristics of all pool demands, the optimization of objective function (9) has been carried out with satisfying all constraints (10)-(11) along with generation offers and demand bidding constraints, which are the maximum limits of offers as well as bids. The proposed approach is capable of handling generating units having any type of cost characteristics such as quadratic, piecewise linear, piecewise quadratic etc. In this paper, quadratic cost characteristics for generators as well as demands are taken for the comparison purpose.

The amount to be paid by each demand and amount to be received by each genco is determined base on most probable bidding price approach. The social welfare has been then determined based on total payments and receipts.

## III. Proposed Sequential Optimization Algorithm

The optimization problem of Eq. (9) is a complex large scale nonlinear programming problem that can not easily be solved by conventional approaches. This paper proposes a sequential optimization approach in order to determine the optimal location, rating and cost of TCSC simultaneously and to capture the best solution of Eq. (9). This approach is based on sequential optimal power flows (SOPF), in which optimization has been done by locating TCSC and varying all control parameters sequentially between the specified ranges and getting optimal solutions. TCSC will be located at all possible locations in the system and best location will be decided at which social welfare and objective function gets maximum value.

### *A. Step-by-step Procedure and Flow Chart of Proposed Approach*

The main steps of proposed algorithm can be described as follows:

Step1: Input power system parameters, including system configuration, line data, bus data and demand/ generator cost coefficients.

Step2: Set the initial number of TCSC is zero (N = 0), compensation level of TCSC is zero ($k_{TCSC} = 0$).

Step3: Solve OPF problem defined by Eq. (9), (10) and (11) without considering TCSC and save the optimal value of objective function $F_{without}$.

Step4: Set line L = 1 and N = N + 1.

Step5: Locate the TCSC at the line L with setting the value of TCSC compensation level ($k_{TCSC} = k_{TCSC}^{min}$).

Step6: Solve OPF problem and determining the optimal value of objective function $F_{with}$.

Step7: Update the value of TCSC compensation level by small increment ($\Delta k_{TCSC}$) and set it to ($k_{TCSC} = k_{TCSC}^{min} + \Delta k_{TCSC}$). Check the value of $F_{with}$ for all $k_{TCSC}$ between the specified ranges.

Step8: Determine maximum value of $F_{with}$.

Step9: Set L = L + 1 and repeat steps 5-8.

Step10: Calculate $\Delta F(L)$, where $\Delta F(L)$ is the maximum value of objective function after placement of TCSC on line $L$.

Step11: Determine optimal value of $k_{TCSC}$, location of TCSC, reactance of TCSC, investment cost of TCSC, operating mode of placed TCSC and social welfare.

The flow chart of the proposed approach is given in Fig. 2. In this figure, $N$ is number of FACTS devices; $k_{TCSC}$ is compensation level of TCSC; $\Delta k_{TCSC}$ is increment in $k_{TCSC}$; $k_{TCSC}^{max}$ is maximum value of $k_{TCSC}$ (0.2); $k_{TCSC}^{min}$ is minimum value of $k_{TCSC}$ (-0.7); $F_{obj}$ is value of objective function; $F_{without}$ is value of objective function without TCSC in the network and $F_{with}$ is value of objective function with TCSC in the network.

### *B. Investment Cost Recovery*

Investment cost of TCSC has been calculated by the equations described in section II-B of this paper. The objective function has two parts: one is social welfare and another part is investment cost of TCSC. The social welfare is combination of the equations for maximization of consumer benefit and minimization of generation cost. By proposed approach, there is considerable increase in social welfare with installation of TCSC. This increase in social welfare is so much that it recovers the installation cost of TCSC. After this recovery, there is no additional revenue will be needed for the TCSC.

## IV. Application of Proposed Algorithm

The proposed approach for optimal location of TCSC has been tested, analyzed and compared on a modified IEEE 14-bus system [16]. The modified IEEE 14-bus system has 5 generators and 20 transmission lines (including 3 transformer branches), in which generator at bus number 8 generates only reactive power.

The results are compared with some of the existing approaches for TCSC placement suggested in [16] and [17]. As per these references, the generator cost and demand benefit functions for both systems are taken as quadratic for comparison purpose.

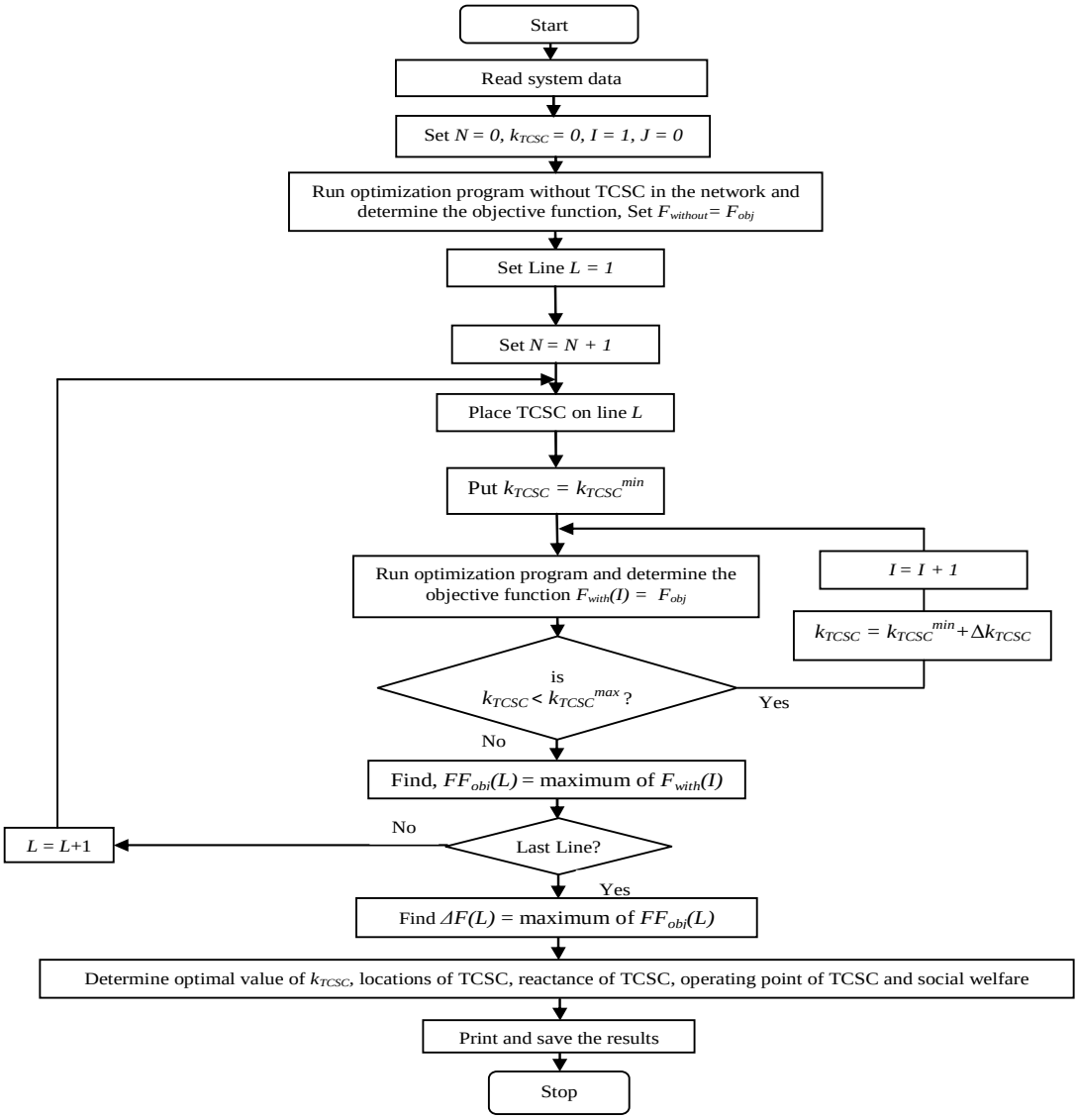


Fig. 2 Flowchart of proposed approach

*A. TCSC Placement in Modified IEEE 14-bus System*

By the proposed approach, first optimization has been performed without considering TCSC in the network and determines the optimal values of objective function and social welfare. After that, the optimization approach (shown in Fig. 2) is applied for considering TCSC in the network in order to find optimal location, objective function and social welfare. In this case the TCSC is located at line number 9 (line segment 4-7) and corresponding social welfare is shown in Table I.

Table I also shows the comparison of proposed technique with fuzzy-GA based approach proposed in [17] and sequential quadratic programming based approach presented in [16], in terms of maximizing social welfare. In [17], the simulation has been done for smooth and nonsmooth generation cost curves but the present work has considered only smooth cost curve for comparison purpose.

TABLE I
COMPARISON OF PROPOSED APPROACH WITH OTHER METHODS

| S. N. | FACTS Allocation Approach | Optimal Location | Social Welfare (Without TCSC) ($/h) | Social Welfare (With TCSC) ($/h) | %age Improvement in Social Welfare ($/h) |
|---|---|---|---|---|---|
| 1 | Fuzzy-GA Approach [17] | Line - 16 | 1577.3 | 1604.57 | 1.73 % |
| 2 | SQP Approach [16] | Line - 17 | | 1595.90 | 1.18 % |
| 3 | Proposed Approach | Line - 9 | | 1725.79 | 9.41 % |

From this table, it can be seen that percentage improvement in social welfare is significant by proposed approach, when TCSC is placed on line number-9 as compared to other approaches in which placement of TCSC is suggested on different lines. Figure 3 shows the graphical representation of

comparison between different approaches in terms of maximization of social welfare. The enhancement in social welfare by proposed approach compared to another approaches can clearly seen by this figure.

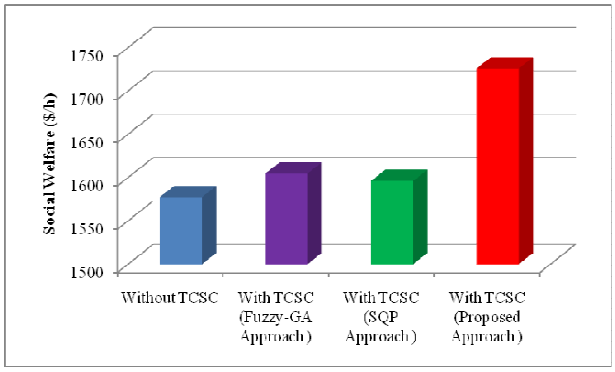


Fig. 3 Social welfare for different cases

The optimal value of location, compensation level, operating mode, reactance and cost of desired TCSC have been determined from optimization technique proposed in Fig. 2, which are presented in Table II.

TABLE II
OPTIMAL PARAMETERS OF PLACED TCSC

| S.N. | TCSC Parameters | Optimal Value/Mode |
|---|---|---|
| 1 | Optimal Location | Line Number 9 |
| 2 | Compensation Level ($k_{TCSC}$) in p.u. | -0.49 |
| 3 | Operating Mode | Capacitive |
| 4 | Reactance of TCSC ($x_{TCSC}$ ) in p.u. | -0.1025 |
| 5 | Cost of TCSC ($/h) | 0.1106 |

This table shows that the operating mode of placed TCSC is capacitive and optimal value of reactance of TCSC is -0.1025 in order to find the best compensation.

Table III provides the comparison of results for additional benefits by all three approaches for modified IEEE 14-bus system. As shown in this table, additional social welfare after investment cost recovery of placed TCSC by proposed approach is 148.3794 $/h. It is more than the additional social welfare of other two approaches in which TCSC investment recovery did not considered.

TABLE III
INVESTMENT RECOVERY BY ADDITIONAL SOCIAL WELFARE

| S.N. | Approach | Items | Value ($/h) |
|---|---|---|---|
| 1. | Base Case for All Approaches | Social Welfare Without TCSC; (A) | 1577.3 |
| 2. | Proposed Approach | Social Welfare With TCSC Allocation at Line Number 9; (B) | 1725.79 |
| | | Additional Social Welfare Without Investment Recovery of TCSC; (C) = (B - A) | 148.49 |
| | | Investment Cost of TCSC; (D) | 0.1106 |
| | | Additional Social Welfare After Investment Recovery of TCSC; (E) = (C - D) | **148.3794** |
| 3. | Fuzzy-GA Approach [17] | Social Welfare With TCSC Allocation at Line Number 16; (F) | 1604.57 |
| | | Additional Social Welfare after Placement of TCSC; (G) = (F - A) | **27.27** |
| 4. | SQP Approach [16] | Social Welfare With TCSC Allocation at Line Number 17; (H) | 1595.90 |
| | | Additional Social Welfare after Placement of TCSC; (I) = (H - A) | **18.6** |

TABLE IV
COMPARISON OF OPTIMAL GENERATION AND LOAD LEVELS

| | Bus Number | Without TCSC | With TCSC for SQP Approach [16] | With TCSC for Fuzzy-GA Approach [17] | With TCSC for Proposed Approach |
|---|---|---|---|---|---|
| | | Optimal Value of Generation and Load (MW) | Optimal Value of Generation and Load (MW) | Optimal Value of Generation and Load (MW) | Optimal Value of Generation and Load (MW) |
| Generator | 1 | 95.6 | 95.9 | 88.84 | 100 |
| | 2 | 100 | 100 | 100 | 190.92 |
| | 3 | 100 | 100 | 100 | 171.57 |
| | 6 | 53 | 55.7 | 63.59 | 100 |
| | **Total** | **348.6** | **351.6** | **352.43** | **562.49** |
| Load | 4 | 107.6 | 107.7 | 107.7 | 188.78 |
| | 5 | 116.2 | 116.2 | 116.2 | 200 |
| | 9 | 5 | 5 | 5 | 5 |
| | 10 | 20.8 | 26.8 | 26.8 | 5 |
| | 11 | 20.7 | 15.4 | 15.4 | 5 |
| | 12 | 26 | 25.9 | 25.9 | 5 |
| | 13 | 5 | 9.2 | 9.2 | 5 |
| | 14 | 29.4 | 29.5 | 29.5 | 5 |
| | **Total** | **331.7** | **335.7** | **335.7** | **418.78** |

Table IV shows the comparison of optimal generation and load levels for all three approaches. This comparison has been takes place for constrained optimization case. From this table, the total optimal generation with proposed approach is 562.49 MW whereas total demand is 418.78 MW. This is more than the total generation as well as demand by another two approaches suggested in [16] and [17]. It means that utilization of the system by proposed optimization technique is more than the other techniques. Therefore, by proposed approach, more generation and demand improves the market activity by selling and buying more electricity through ISO and improves the social welfare with relieving the congestion.

In order to assess the computational burden of the proposed optimization technique, the total CPU time was measured for the simulation carried out on a computer with Pentium-IV, 3.20-GHz and 512 MB of RAM. The overall CPU time is found as 482.27 seconds (even after running optimization many times) for the modified IEEE 14-bus system.

The following observations have been made by the simulation with the proposed technique:

1) Simulation time of the proposed optimization technique is very less in comparison to other existing heuristic optimization techniques.
2) In [8], optimal location of TCSC and static var compensator (SVC) has been determined by a hybrid particle swarm optimization (HPSO) technique. They have studied and analyzed the results on IEEE 14-bus

and IEEE 30-bus systems with different number of particles. The simulation time in this case is 2.74 hours, 5.22 hours and 8.07 hours for 20, 40 and 60 number of particles respectively. These times are very huge in comparison to proposed method in this paper.

3) By proposed approach, there is considerable increase in social welfare with installation of TCSC. The increase in social welfare is so much that it even covers the installation cost of TCSC. In other words, the installation cost of TCSC is recovered from enhanced social welfare. Therefore no additional revenue is required for the FACTS device in this optimal approach.
4) The proposed technique not only provides the unique optimal location of TCSC but also determines the optimal parameters of TCSC.

## V. Conclusion

This paper proposed a fast and efficient sequential optimization technique for simultaneously determining the optimal location and parameter of TCSC in the deregulated power sector. The test results demonstrate the effectiveness of the proposed approach in terms of maximizing the social welfare with minimizing the TCSC installation cost, recovers the TCSC investment cost and enhancing market trading capability by allowing more generation and demand through the network. The proposed method of optimal placement of TCSC has provided better results as compared to the SQP approach suggested in [16] and fuzzy-GA approach in [17]. Furthermore, the proposed approach is very fast and accurate in comparison to other previous heuristic and metaheuristic optimization approaches [8].

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