Influence of TCSC Devices on Congestion Management in a Deregulated Power System Using Evolutionary Programming Technique

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ABSTRACT:
Congestion management is one of the technical challenges in power system deregulation. In deregulated electricity market it may always not be possible to dispatch all of the contracted power transactions due to congestion of the transmission corridors. Transmission congestion occurs when there is insufficient transmission capacity to simultaneously accommodate all constraints for transmission of a line. Flexible Alternative Current Transmission System (FACTS) devices can be an alternative to reduce the flows in the heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flow in the network. A method to determine the optimal location of FACTS has been suggested based on reduction of total system VAR power losses. The simulation was done on IEEE 14 bus system and results were obtained.

Keywords: Congestion management, Flexible alternative current transmission system (FACTS), Thyristor Controlled Series Capacitor (TCSC), sensitivity analysis, MATLAB.

1. Introduction
Electricity market activities and a growing demand for electricity have led to heavily stressed power systems. This requires operation of the networks closer to their stability limits. Power system operation is affected by stability related problems, leading to unpredictable system behaviour [1]. Cost efficient solutions are preferred over network extensions. In many countries, permits to build new transmission lines are hard to get, which means the existing network has to be enforced to fulfil the changing requirements.

2. Transmission Network and Congestion
The first important step of power industry restructuring is the transmission open access. Transmission services have been unbundled as separate business from generation. However regarded as a natural monopoly, the transmission sector remains more or less regulated to
permit a competitive environment for generation and retail services [2]. The operating and planning of transmission network and the pricing of the transmission services are still retained as challenges on both theoretical and practical aspects in the development of electricity markets. Transmission congestion can be defined as the condition where desired transmission line-flows exceed reliability limits. Following this definition, congestion management can be defined as the actions taken to avoid or relieve congestion. More broadly, congestion management can be considered any systematic approach used in scheduling and matching generation and loads in order to manage congestion. With transmission limits, the deregulation of the power industry is more difficult therefore one of the major responsibilities of any type of SOs in any type of electricity markets is to manage transmission congestion and constraints.

The function of transmission system in a vertically integrated structure was to connect the utility’s generator to the utility customers and to operate the system reliably. The transmission systems were interconnected by different utilities to increase reliability, share reserves and take advantage of economic exchanges. If transmission congestion occurred, the utilities solved it by either generation re-dispatch or load-reduction to support reliability and economic transactions. These corrective actions and also expectations for load growth, future electricity prices and availability were a feedback for system evaluation in both a real-time basis and long-term planning purposes. Although, the electric power industry restructuring has moved generation investment and operation decisions into the competitive market but transmission was left out as a communal resource in the regulated environment and despite the widespread experience of restructuring during the past decade, important issues remain open about the best way to operate transmission to support reliability management and market trading. In some models the mixing of competitive generation and regulated transmission makes congestion management difficult and in some other models the huge quantity of bilateral transactions which could stress the existing transmission network heavily, has made the transmission congestion management as one of the toughest problems in electricity market design and operation.

3. Congestion Management

Congestion is a term that has come to power systems from economics in conjunction with deregulation, although congestion was present on power systems before deregulation. Congestion management controls the transmission system so that transfer limits are observed, perhaps the fundamental transmission management problem [3]. The term “congestion management” comprises all actions and measures that are applied to handle network access in the presence of congestion. Before regulation, the transmission system was designed so that when the generation was dispatched economically there would be no limit violations. Hence, just solving economic dispatch was usually sufficient. However, with the deregulation of the electric utility industry, the transmission system is becoming increasingly constrained as a result of moving more power through a transmission line (or an interface) can accommodate, for either reliability or commercial reasons. A consequence of a congested interface or cross-
Congestion relief through transmission enhancements is desirable if it is cost-effective. There are usually several alternatives to relieve congestion and the goal should be to devise systems of incentives that produce cost-effective means to reduce such congestion where it is economical to do so. From the viewpoint of planning, effective relief methods can include installation and/or operation of large or small-scale generation in the congested area for energy production, for voltage support, to enhance stability, or to reduce flows on specific lines. Transmission-based solutions can include construction of new lines or facilities, upgrading of lines or facilities, installation of voltage support (capacitors, inductors, voltage regulating transformers, static condensers, or static VAr compensators), or installation of flow-control devices (phase angle regulators or FACTS devices), and power system stabilizers at generating stations. The technologies allow more power to be delivered over a line or to operate the system more reliably. Load management approaches can also provide congestion relief under certain circumstances. The incentives (and moreover, disincentives) for a particular type of relief depend on various economic, technical, informational, and regulatory elements. Different market structures and market rules lead to different methods for congestion management.

4. Facts Devices Overview

Power system engineers are currently facing challenges to increase the power transfer capabilities of existing transmission system. This is where the Flexible AC Transmission System (FACTS) technology comes into effect. With relatively low investment, compared to new transmission or generation facilities, the FACTS technology allows the industries to better utilize the existing transmission and generation reserves, while enhancing the power system performance [4]. Moreover, the current trend of deregulated electricity market also favours the FACTS controllers in many ways. FACTS controllers in the deregulated electricity market allow the system to be used in more flexible way with increase in various stability margins. FACTS controllers are products of FACTS technology; a group of power electronics controllers expected to revolutionize the power transmission and distribution system in many ways. The FACTS controllers clearly enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources. Thyristor Controlled Series Capacitor (TCSC) is a key FACTS controller and is widely recognized as an effective and economical means to enhance power system stability. For the FACTS side the taxonomy in terms of 'dynamic' and 'static'. The term 'dynamic' is used to express the fast controllability of FACTS-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS-devices can equally be static and dynamic.

A. Configuration of Thyristor Controlled Series Capacitor (TCSC)
TCSC addresses specific dynamical problems in transmission systems. First it increases damping when large electrical systems are interconnected. Second it can overcome the problem of Sub- Synchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems [5]. The TCSC’s high speed switching capability provides a mechanism for controlling line power flow, which permits increased loading of existing transmission lines, and allows for rapid readjustment of line power flow in response to various contingencies.

The TCSC also can regulate steady-state power flow within its rating limits. From a principal technology point of view, the TCSC resembles the conventional series capacitor. All the power equipment is located on an isolated steel platform, including the Thyristor valve that is used to control the behaviour of the main capacitor bank. Likewise the control and protection is located on ground potential together with other auxiliary systems. Figure 1 shows the principle setup of a TCSC and its operational diagram. The firing angle and the thermal limits of the Thyristors determine the boundaries of the operational diagram.

The main principles of the TCSC concept are two; first, to provide electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line, i.e. the TCSC will provide a variable capacitive reactance. Secondly, the TCSC shall change its apparent impedance (as seen by the line current) for sub-synchronous frequencies, such that a prospective sub-synchronous resonance is avoided. Both objectives are achieved with the TCSC, using control algorithms that work concurrently. The controls will function on the Thyristor circuit in parallel to the main capacitor bank such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency but a “virtual inductor” at sub-synchronous frequencies.

5. Methodology and Procedure
A. Static Modeling of FACTS Devices and Formulation
The Figure 2 shows a simple transmission line represented by its lumped p equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-i and bus-j are $V_i$, $\delta_i$ and $V_j$, $\delta_j$ respectively. The real and reactive power flow from bus-i to bus-j can be written as
Where $\delta_{ij} = \delta_i - \delta_j$. Similarly, the real and reactive power flow from bus-j to bus-i is given in equations (1) and (2).

$$P_{il} = V_i^2 G_{ij} - V_i V_j [G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})]$$

(1)

$$Q_{il} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})]$$

(2)

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Figure 3. During the steady state the TCSC can be considered as a static reactance $c - jx_c$. The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a line having series impedance and a series reactance $-jx_c$. The real and reactive power flow from bus-i to bus-j, and from bus-j to bus-i of a line having series impedance and a series reactance are in equation (3), (4), (5) and (6).

$$Z_{ij} = r_{ij} + jx_{ij}$$

(3)

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})]$$

(4)

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})]$$

(5)

$$P_{ij}^\prime = V_j^2 G_{ij} - V_i V_j [G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij})]$$

(6)

$$Q_{ij}^\prime = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij})]$$

Where $G_{ij}'$ and $B_{ij}'$ are given in equation (7) and (8).
The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending end of the line as shown in Figure 4. The real and reactive power injections at bus-i and bus-j can be expressed as in equations (9), (10) and (11).

\[
P_{jc} = V_j^2\Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos(\delta_{ij}) + \Delta B_{ij} \sin(\delta_{ij})]
\]

\[
Q_{lc} = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin(\delta_{ij}) - \Delta B_{ij} \cos(\delta_{ij})]
\]

\[
Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin(\delta_{ij}) + \Delta B_{ij} \cos(\delta_{ij})]
\]

Where \(\Delta G_{ij}\) and \(\Delta B_{ij}\) are given in equations (12) and (13)

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

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

Figure 4. Injection model of TCSC

Due to high cost of FACTS devices, it is necessary to use cost-benefit analysis to analyze whether new FACTS device is cost effective among several candidate locations where they actually installed. The TCSC cost in line-k is given in equation (14).

\[
C_{TCSC}(k) = c_x x_c(k) P_{L}^2 \text{Base } \text{power}
\]

Where \(c\) is the unit investment cost of FACTS, \(x_c(k)\) is the series capacitive reactance, \(P_L\) is the power flow in line-k and base power is taken as 100 MVA. The objective function for placement of TCSC will be in equation (15).

\[
\text{Min } \sum_i C_i (P_i) + C_{TCSC}
\]
B. Optimal Location of TCSC

1) Reduction of Total System Reactive Power Loss

Here we look at a method based on the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC [6]. For TCSC placed between buses i and j we consider net line series reactance as a control parameter. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as equation (16).

\[ a_{ij} = \frac{\partial Q}{\partial x_{ij}} = \left[ V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij} \right] \frac{r_{ij}^2 - x_{ij}^2}{r_{ij}^2 + x_{ij}^2} \]  

(16)

2) Real Power Flow Performance Index Sensitivity Indices

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index, as given in equation (17).

\[ PI = \sum_{m=1}^{N_L} \frac{w_m}{2^n} \left( \frac{P_L}{P_{Lm}^{max}} \right)^{2n} \]  

(17)

Where \( P_L \) is the real power flow and \( P_{Lm}^{max} \) is the rated capacity of line-m, \( n \) is the exponent and \( w_m \) a real non-negative weighting coefficient which may be used to reflect the importance of lines. PI will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for given state of the power system. Most of the works on contingency selection algorithms utilize the second order performance indices which, in general, suffer from masking effects. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order performance indices, that is \( n > 1 \). However, in this study, the value of exponent has been taken as 2 and \( w = 1 \). The real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as equation (18).

\[ b_k = \frac{\partial PI}{\partial x_{ck}} \bigg|_{x_{ck}} = 0 \]  

(18)

The sensitivity of PI with respect to TCSC parameter connected between bus-i and bus-j can be written as equation (19).

\[ \frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m \left( \frac{1}{P_{Lm}^{max}} \right)^4 \frac{\partial P_L}{\partial x_{ck}} \]  

(19)
The real power flow in a line-\( m \) can be represented in terms of real power injections using DC power flow equations (20) where \( s \) is slack bus.

\[
P_{Lm} = \begin{cases} 
\sum_{n=1}^{N} s_{mn} P_{n form} & \text{if } k \\
\sum_{n=1}^{N} s_{mn} P_{n} + P_{j form} & \text{if } k
\end{cases}
\]  

(20)

Where \( s_{mn} \) is the \( mn^{th} \) element of matrix \( [S] \) which relates line flow with power injections at the buses without TCSC devices and \( N \) is the number of buses in the system. Observe that line \( k \), from bus-\( i \) to bus-\( j \), is the line containing the TCSC device. \( P_j \), therefore is the additional flow, at bus-\( j \), in the line containing the TCSC device, due to the presence of the device. Using the above equation, the following relationship can be derived as equation (21).

\[
\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} 
\left( s_{mi} \frac{\partial P_i}{\partial x_{ck}} + s_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) & \text{if } k \\
\left( s_{mi} \frac{\partial P_i}{\partial x_{ck}} + s_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) + \frac{\partial P_l}{\partial x_{ck}} & \text{if } k
\end{cases}
\]  

(21)

The terms \( \frac{\partial P_i}{\partial x_{ck}} \mid x_{ck} = 0 \) and \( \frac{\partial P_j}{\partial x_{ck}} \mid x_{ck} = 0 \) can be obtained using the equation (22) and (23).

\[
\frac{\partial P_i}{\partial x_{ck}} \bigg|_{x_{ck}=0} = \frac{\partial P_i}{\partial x_{ck}} \bigg|_{x_{ck}=0}
\]

\[
= -2 \left( V_i^2 - V_i V_j \cos \delta_{ij} \right) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)} - V_i V_j \sin \delta_{ij} \frac{x_{ij}^2 - r_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2}
\]  

(22)

\[
\frac{\partial P_j}{\partial x_{ck}} \bigg|_{x_{ck}=0} = \frac{\partial P_j}{\partial x_{ck}} \bigg|_{x_{ck}=0}
\]

\[
= -2 \left( V_j^2 - V_i V_j \cos \delta_{ij} \right) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)} + V_i V_j \sin \delta_{ij} \frac{x_{ij}^2 - r_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2}
\]  

(23)

3) Criteria for Optimal Location

The FACTS device should be placed on the most sensitive line with the sensitivity indices computed for TCSC, following criteria can be used for its optimal placement [7].

- In reactive power loss reduction method TCSC should be placed in a line having the most positive loss sensitivity index.
- In PI method TCSC should be placed in a line having most negative sensitivity index.

6. Evolutionary Programming Technique
A. The Evolutionary Programming Optimization Technique

The main functions of the EP method include Initialization, Mutation and Recombination. First create initial population for given specified range. A set of new population can be formulated from a set of existing population through the use of a mutation operator function. The new candidate solutions or individuals are determined by its fitness function which can be defined as an objective function of the problem. Through the use of a competition scheme, the individuals in each population compete with each other. The winning individuals will form a set of best population which is regarded as the next generation. Through this the population evolves towards the global optimal point solution. Based on the EP method, the algorithm for solving the optimal generation scheduling problem can be established [8].

1. Initialization

The initial population can be generated randomly using sets of uniform random number distribution ranging over the limits of each control variable in equation (24).

$$ x_i = x_i^{\text{min}} + u(x_i^{\text{max}} - x_i^{\text{min}}) $$

Where \( x_i \) is the \( i \)th element of the individual in a population. Min \( x_i \) and Max \( x_i \) are the lower and upper limits of the \( i \)th element of the individual. The 'u' is a random number in the interval [0, 1].

2. Fitness Function

The fitness function of the \( k \)th individual can be calculated by equation (25).

$$ f_k = K_f * F' $$

Where \( f_k \) is the fitness function of the \( k \)th individual, \( K_f \) is an arbitrary constant, and \( F' \) is the objective function.

3. Mutation

A new population can be generated by using the Gaussian mutation operator. Each element of the \( k \)th new trial solution vector can be computed as in equations (26) and (27).

$$ x_{k,l}' = x_{k,l} + N(0, \sigma^2_{x_{k,l}}) $$

$$ \sigma_{x_{k,l}} = (x_{l}^{\text{max}} - x_{l}^{\text{min}}) \left( \frac{f_{\text{max}} - f_k}{f_{\text{max}}} + a \right) $$

Where \( x_{k,l}' \) is the \( l \)th element of the \( k \)th offspring individual. The \( x_{k,l} \) is the \( l \)th element of the \( k \)th parent individual. The \( N(0, \sigma^2_{x_{k,l}}) \) is a Gaussian random number with a mean of zero and standard deviation of \( k, l \). The \( x_{l}^{\text{min}} \) and \( x_{l}^{\text{max}} \) are the lower and upper limits of the \( l \)th element of the \( k \)th parent individual. The \( f_k \) is the fitness of the \( k \)th individual. The \( f_{\text{max}} \) is the maximum fitness of the parent population. The 'a' is a positive number constant slightly less than one and 'g' is the iteration counter.
4. Selection

The selection technique utilized is a tournament scheme, which can be expressed as in equations (28) and (29).

\[ w_t = \begin{cases} 
1 & \text{if } f_k > f_r \\
0 & \text{otherwise}
\end{cases} \quad (28) 
\]

\[ S_k = \sum_{t=1}^{N_t} w_t \quad (29) \]

Where \( f_k \) is the fitness function of the \( k \)th individual in the combined population, the \( f_r \) is the fitness function of the \( r \)th opponent randomly selected from the combined population based on \( r = \lfloor 2 \times P \times u + 1 \rfloor \) is the greatest integer less than or equal to \( x \). The ‘\( u \)’ is a uniform random number in the interval [0, 1] and \( P \) is the population size.

5. Termination Criterion

If the maximum number generation (iteration) is reached, the iteration process can be terminated. Otherwise, the mutation and selection operation will be repeated until the solution is satisfied.

7. Results

The approach has been examined on an IEEE 14-bus system. MATPOWER 4.1, a toolbox of MATLAB, has been used for simulation [9]. The prices bid by generators for 14-bus system are given in Table I where \( P \) is in MW and $ is a momentary unit which may be scaled by any arbitrary constant without affecting the results and \( P_{i\min} \), \( P_{i\max} \) are generation power limits of each generator.

| Generator | Bid prices | \( P_{i\min} \) | \( P_{i\max} \) |
|-----------|------------|----------------|----------------|
| 1         | 0.11\( P_1^2 \)+5\( P_1 \)+150 | 0 | 300 |
| 2         | 0.085\( P_2^2 \)+1.2\( P_2 \)+60 | 0 | 200 |
| 3         | 0.1225\( P_3^2 \)+1.2\( P_3 \)+335 | 0 | 200 |

| Line | i-j | \( a_{ij} \) |
|------|-----|-------------|
| 1    | 1-2 | -1.783      |
| 2    | 2-3 | -0.4431     |
| 3    | 2-4 | -0.2280     |
| 4    | 1-5 | -0.4524     |
| 5    | 2-5 | -0.1266     |
| 6    | 3-4 | -0.0430     |
| 7    | 4-5 | -0.3065     |
The sensitivities of reactive power loss reduction and real power flow performance index with respect to TCSC control parameter has been computed and are shown in Table II. The sensitive line in each case is presented in bold type. It is observed from Table II that placement of TCSC in line-19 and line-20 is suitable for reducing the total reactive power loss. System power flow result after placing TCSC in line-19 is shown in Table III. The value of control parameter of TCSC for computing power flow is taken as 0.0423. According to method - 2 as shown in Table IV, the most negative value of $b_{ij}$ tells us about the line where to keep the TCSC. In the previous tabulation, the most negative values of $b_{ij}$ have been highlighted. The values are -0.6536 and -0.4290 for the lines 1 and 16. These two lines are suitable for the placement of TCSC.

**TABLE III**

| Line | i-j | Power flow without TCSC (p. u.) | Power flow with TCSC (p. u.) |
|------|-----|-------------------------------|-------------------------------|
| 1    | 1-2 | 1.5673                        | -1.4780                       |
| 2    | 2-3 | 0.7336                        | -0.1872                       |
| 3    | 2-4 | 0.5564                        | -0.1474                       |
| 4    | 1-5 | 0.7534                        | -0.1660                       |
| 5    | 2-5 | 0.4132                        | -0.1152                       |
| 6    | 3-4 | -0.2400                       | 0.0558                        |
| 7    | 4-5 | -0.5991                       | -0.5795                       |
| 8    | 5-6 | 0.4119                        | -0.0831                       |
| Line | i-j       | \(b_{ij}\)  |
|------|-----------|-------------|
| 9    | 4-7       | 0.2761      |
|      |           | -0.0700     |
| 10   | 7-8       | 0.0000      |
|      |           | 0.0000      |
| 11   | 4-9       | 0.1564      |
|      |           | -0.0129     |
| 12   | 7-9       | 0.2801      |
|      |           | -0.1755     |
| 13   | 9-10      | 0.0569      |
|      |           | -0.0543     |
| 14   | 6-11      | -1.9397     |
|      |           | 0.1784      |
| 15   | 6-12      | 0.0683      |
|      |           | -0.0142     |
| 16   | 6-13      | 0.1780      |
|      |           | 0.0720      |
| 17   | 9-14      | 0.0939      |
|      |           | 0.0160      |
| 18   | 10-11     | -2.1689     |
|      |           | 0.2735      |
| 19   | 12-13     | 0.0166      |
|      |           | 0.0025      |
| 20   | 13-14     | 0.0551      |
|      |           | 0.0067      |

**TABLE IV**

\(b_{ij}\) Values for the 14 Bus IEEE System

A. Cost of generation
Evolutionary programming technique has been used for getting the optimum values of power output with and without using TCSC device and not exceeding the generating limits. The optimum values thus obtained are given in Table V and Table VI.

**TABLE V**  
Generation Output

| Generation | Generation(MW) Without TCSC | Generation(MW) With TCSC |
|------------|-----------------------------|--------------------------|
| P₁         | 70.0629                     | 69.6535                  |
| P₂         | 113.5507                    | 111.6848                 |
| P₃         | 76.3911                     | 78.6639                  |

**TABLE VI**  
Generation Cost

| S.No | Location of TCSC   | Cost of Generation($/hr) |
|------|--------------------|--------------------------|
| 1    | Without TCSC       | 3258.8                   |
| 2    | TCSC in line-19    | 3257.9                   |

![Figure. 5. Cost Vs Iterations before placing TCSC (Evolutionary Programming)](image)

![Figure. 6. Cost Vs Iterations after placing TCSC (Evolutionary Programming)](image)
8. Conclusions

The operational aspects of power systems pose some of the most challenging problems encountered in the restructuring of the electric power industry. This paper focuses on congestion management within an OPF framework in a deregulated electricity market scenario. Congestion management is an important issue in deregulated power systems. FACTS devices such as TCSC by controlling the power flows in the network can help to reduce the flows in heavily loaded lines. Because of the considerable costs of FACTS devices, it is important to obtain optimal location for placement of these devices. In this report sensitivity of each line is computed and based on sensitivity factor, the optimal placement of TCSC Device have been determined. In a system, first two optimal locations of TCSC can be achieved based on the sensitivity factor aij and then optimal location is selected based on minimizing production cost plus device cost. Test results obtained on IEEE 14-bus power systems show that sensitivity factors along with TCSC cost could be effectively used for determining optimal location of TCSC. Future work in this field may focus on quantifying the economic risk faced by market players due to differences in their willingness to pay to avoid curtailment. Research may also be carried out on designing different dispatch and curtailment strategies. The sensitivity approach for determining optimal locations of FACTS devices can give best approximate idea about the optimal location for those devices in a deregulated environment.

Appendix

1. IEEE 14-Bus System
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