Genetic Algorithm based Congestion Management by Employing Multi-type FACTS in a Deregulated Environment

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Abstract— In a deregulated environment, it may not always possible to deliver a contracted power due to the violation of system operating limits, it creates congestion in a transmission system. Flexible AC transmission systems (FACTS) devices can be an alternative to reduce the flows in heavily loaded lines resulting in an increased load ability, low system loss, improved stability and reduced cost of production. In this work, Multi objective congestion management is proposed. The objectives are to minimize the transmission losses, performance index, congestion cost and to maximize the voltage stability margin. Based on the real power performance index sensitivity method, the locations for the FACTS device are chosen. The voltage stability margin is increased using Voltage Stability Index (VSI). Genetic Algorithm (GA) gives a global optimal solution for a congestion management problem which is based on the nature of chromosomes. This has been performed on an IEEE 30 bus test system in MATLAB environment and the total congestion cost is evaluated by the genetic algorithm optimization technique. Finally, the congestion cost is compared by generator rescheduling method and the application of FACTS devices in the transmission line.

Key words: Deregulation, Congestion Management, Generator Rescheduling, Flexible AC Transmission System (FACTS) devices, Thyristor Controlled Series Capacitor (TCSC), Static VAR Compensator (SVC), Voltage Stability, Genetic Algorithm

I. INTRODUCTION

The demand for electricity is tremendously increases day to day because of the growth of population. So there may be a need to enhance the existing power system or establish the new system to supply the power to meet the demands. However, the expansion of the transmission system is a quite complex one and the capital cost is also increased. So the enhancement of the existing power system is the choice. In a deregulated electricity market, the independent system operator (ISO) must ensure that contracted power transactions are carried out reliable manner. Due to the large number of transactions the transmission networks may easily get congested [1]. To relieve the congestion ISO uses the following congestion management techniques:

A. Cost-Free Methodology

- Outaging of congested transmission lines.
- Operation of transformer taps or phase shifters.
- Operation of FACTS controllers, particularly series devices.

B. Non-Cost-Free Methodology

- Re-Dispatching of power generation.
- Curtailment of loads.

Various methodologies had been proposed in the literature. Keshi *et al* [2] proposed the congestion management approach by the emerging FACTS devices like TCSC and UPFC. LMP differences and congestion rent methods are used to find the best locations for the FACTS devices in [3]. LMPs are the by-product of a security constrained OPF and congestion rent is a function of LMP difference and power flows.Srinivasa rao et al [4] presented that the optimal location of TCSC using sensitivity factor based approach.Thesensitivity of the congested line flow with respect to flow in other lines has used for the placement of the TCSC. In [5], the optimal placements of FACTS device are based on a real power performance index and reduction of total system VAR power lossesto minimize the congestion cost.All the above mentioned works has not been considered the stability improvement. Rony *et al* [6]proposed the multi objective particle swarm optimization (MOPSO) technique to optimize the generation cost and installation cost while satisfying minimum load margin.

Tabatabaei *et al* [7] described the adaptive particle swarm optimization mixed with simulated annealing (APSO-SA) to decrease the cost of investment & real power losses and toimprove the voltage stability index. A methodbased on line stability index, real power performance index and reduction of total system VAR power losses have proposed to decide the optimal location of TCSC in [8].Biswas*et al* [9] proposed the modified differential evolution procedure to minimize the real power loss and reactive power generation. Kiran *et al* [10] presented the sensitivity of total real power transmission loss with respect to the control parameters of devices to locate the SVC and TCSC to minimize the losses, increases available capacity and improves the voltage profile.Esmaili *et al* [11] presented the location of series FACTS devices to minimize congestion cost and to improve the voltage and transient stability margin. A genetic algorithm is a widely accepted effective optimization method to solve various engineering problems compared to all other conventional methodologies.

In this manuscript, location of FACTS devices has been selected to optimize the real power losses, performance index, congestion cost and voltage stability index. This has been performed in an IEEE 30 bus test system. The manuscript is arranged as follows: Section II briefly describes about the problem formulation for congestion management. Section III details the modelling of FACTS devices. Section IV describes the implementation of congestion relief using GA. Section V details the simulation results and the manuscript are concluded in section VI.

II. PROBLEM FORMULATION

The congestion management problem formulation can be divided into two steps. The first step is the identification of FACTS devices location by using the sensitivity analysis i.e., real power flow performance index. The second step is the optimization ofobjective functions using genetic algorithm.

A. Sensitivity Analysis

Theseverities of the system loading under normal and contingency cases are identified by the real power flow performance index value [12].The sensitivity factor method is done to determine the location to enhance the static performance of the system. The FACTS devices should be placed on the most sensitive line.

$$\text{Performance index, PI}=\sum_{i=1}^{N_l}\frac{W_m}{2n}\left(\frac{P_{Lm}}{P_{Lm}^{max}}\right)^{2n} \quad (1)$$

Where

W_m is the real non-negative weighting coefficient.

P_{Lm} is the real power flow.

P_{Lm}^{max} is the rated capacity of line m.

n is the exponent.

The PI value will be small when all the lines are within their limits and high when there are overloads.Thus, it provides a good measure of severity of the line overloads for a given state of the power system.The real power flow *PI* sensitivity factors with respect to the parameters of TCSC can be defined as,

$$b_k=\frac{\partial PI}{\partial x_{ck}}|\, x_{ck=0} \quad (2)$$

TCSC should be placed in a line having the most negative sensitivity index.

B. Objective Function

1) Congestion cost

The first objective function is to minimize congestion cost CG

$$CG=\sum_{g=1}^{ng}\Delta CP_{gu}+\sum_{g=1}^{ng}\Delta CP_{gd}(3)$$

where

$$\Delta CP_{gu}=C_{gi}*\Delta P_g^{up}(4)$$

$$\Delta CP_{gd}=C_{gd}*\Delta P_g^{down}(5)$$

where

C_{gi} is the incremental bid cost of the generators per MW

$C_{gdv}$is the decremental bid cost of the generators per MW

2) Voltage Stability Index (VSI)

Voltage Stability Index is used to calculate the stability indices for all the load buses connected in an IEEE 30 bus system [13]. For a given system operating condition, by using the load flow results obtained from Newton Raphson Technique, the L index for load buses is to be computed as,

$$L_j=|1-\sum_{i=1}^{g}F_{ij}\frac{V_i}{V_j}|(6)$$

where

n is the total number of buses.

g is the number of generators connected in the system and j=g+1….n.

V_i is the complex voltage at generator bus i.

V_j is thecomplex voltage at load bus j.

F_{ij} is obtained from the Y bus matrix.

$$F_{ij}=[Y_{LL}]^{-1}[Y_{LG}] \quad (7)$$

Where, Y_{LL} and $Y_{LG}$are corresponding partitioned portions of the Y bus matrix.

A L-index value far away from 1 and close to 0 indicates the voltage stability level.If the L index value is moving towards zero, then the system is considered to be stable and improves the system security. When this index value moves away from zero, the stability of the systemis decreased, then the system is considered to be unstable.

3) Calculation of losses

The third objective function considering the minimization of real power loss

$$\text{Losses}=\sum_{i=1}^{n}P_{loss,\,i}(8)$$

where, n is the number of lines in the system.

4) Fuel cost of generators

The fourth objective function is the minimization of fuel cost of generators.

$$\text{Fuel cost}=\sum_{i=1}^{n}a_i P_{Gi}^2+b_iP_{gi}+c_i \quad (9)$$

where

n is the number of generators

$P_{gi}$is the generated power of i_{th} generator

a_i, b_i and $c_i$are the cost coefficients of i_{th} generator ($/MWh)

The Objective function is coded mathematically as,

$$f(x)=max(L_j)+min(Losses)+min(PI)+min(fuel\ cost)+min(CG)(10)$$

where, L_j is the Stability index for the loads connected in the IEEE 30 bus system.

C. Constraints

The constraints which have included in the problem is as follows:

$$\text{Power flow limits: } P_{Gi}^{min}\le P_{Gi}\le P_{Gi}^{max};\ i\in N_B \quad (11)$$

$$Q_{Gi}^{min}\le Q_{Gi}\le Q_{Gi}^{max};i\in N_B \quad (12)$$

$$\text{Voltage limits: } V_i^{min}\le V_i\le V_i^{max}\ ;i\in N_B \quad (13)$$

$$\text{Line flow limits: } S_l\le S_l^{max} \quad (14)$$

FACTS devices constraints:

$$\text{TCSC reactance limits: } X_{TCSC}^{min}\le X_{TCSC}\le X_{TCSC}^{max} \quad (15)$$

$$\text{SVC reactive power limits, } Q_{MVar}^{min}\le Q_{MVar}\le Q_{MVar}^{max}(16)$$

where

V_i^{min} and V_i^{max} are the minimum and maximum limits of the voltage at bus i.

S_l^{max} is the line flow limit of each line in the network.

X_{TCSC}^{min} and X_{TCSC}^{max} are the minimum and maximum reactance limits of the TCSC device.

Q_{MVar}^{min} and Q_{MVar}^{max} are the minimum and maximum reactive power limits of the SVC device.

D. FACTS Device Cost Function

Using [14], the FACTS device cost functions are defined as,

TCSC: C_{TCSC} =0.0015s²-0.71s+153.75 (US$/kVar) (17)

SVC:C_{SVC}=0.0003s^2-0.3051s+127.38 (US$/kVar)(18)

where,

s is the operating range of FACTS devices in MVar.

$$s=|Q_2-Q_1|(19)$$

Q1 – MVar flow through the branch before placing FACTS device.

Q2 - MVar flow through the branch after placing FACTS device.

III. MODELLING OF FACTS DEVICES

The concept of FACTS as a total network control philosophy was introduced in 1988 by Dr. N. Hingorani [15]. It can able to control the various electrical parameters such as voltage magnitude, the phase angle and impedances of transmission line. It gives the advantages like control of power flow, improving voltage stability, limiting short circuit currents. The four categories of FACTS family are series, shunt, series-series and combined series shunt controllers. A series controller (TCSC) and a shunt controller (SVC) are dealt in this paper.

A. *Thyristor Controlled Series Capacitor (TCSC)*

Thyristor Controlled Series Capacitors (TCSC) consists of a fixedcapacitor in parallel with a thyristor controlled reactor [16]. The primary function of the TCSC is to provide variable series compensation to a transmission line. This changes the line flow due to changes in series reactance. The controllable reactance $x_c$is directly used as the control variable to be implemented in the power flow equation. The basic model and the equivalent circuit of TCSC are shown in Fig.1 and 2.

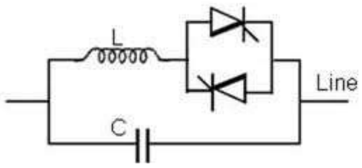
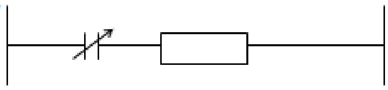


Fig. 1: Basic model of TCSC

i$r_{ij} + jx_{ij}$ j



The power flow equations of branch can be derived as follows

$$P_{ij}=V_i^2 g_{ij}\text{-}V_iV_j\left(g_{ij}\cos\delta_{ij}+b_{ij}\sin\delta_{ij}\right) \qquad (20)$$

$$Q_{ij}=-V_i^2 b_{ij}\text{-}V_iV_j\left(g_{ij}\sin\delta_{ij}-b_{ij}\cos\delta_{ij}\right) \qquad (21)$$

where $V_i$and $V_j$are voltages of i[th]and j[th]bus respectively.

where,

$$g_{ij}=r_{ij}/({r_{ij}}^2+(x_{ij}-x_c)^2) \qquad (22)$$

$$b_{ij}=x_{ij}-x_c/\,({r_{ij}}^2+(x_{ij}-x_c)^{\,2}) \qquad (23)$$

The rating of TCSC depends on the reactance of the transmission line where the TCSC is located:

$$X_{ij}=X_{Line}+X_{TCSC} \qquad (24)$$

$$X_{TCSC}=r_{TCSC}.X_{Line} \qquad (25)$$

where

X_{Line} is the reactance of the transmission line and$r_{TCSC}$is the compensating factor of TCSC which is chosen between -0.8$X_{Line}$to 0.2X_{Line}.

B. *Static VAR Compensator (SVC)*

Static VAR Compensator (SVC) is a shunt connected device, which consists of a Thyristor Controlled Rectifier (TCR) in parallel with a bank of capacitor [16]. The basic SVC model is shown in Fig.3. It regulates the voltage magnitude at which it is connected by either generating or absorbing the reactive power. It is mainly used to provide fast reactive power and voltage regulation support. The SVC reactive power rating is chosen between -100MVar to 100MVar.

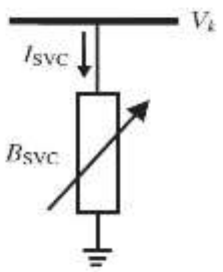


Fig. 3: Basic model of SVC

The current drawn by the SVC is given in (24).

$$I_{SVC}=jB_{SVC}V_k(26)$$

where $B_{SVC}$is the susceptance of SVC and $V_k$is thevoltage at bus k.

The active and reactive power flow equations of SVC are given in (25) and (26).

$$P_{Gi}-P_{Di}=V_i\sum_{k=1}^{r}[V_k\,G_{ik}\cos(\theta_i-\theta_k)+B_{ik}\sin(\theta_i-\theta_k)]](27)$$

$$Q_{Gi}-Q_{Di}=V_i\sum_{k=1}^{r}[V_k\,G_{ik}\sin(\theta_i-\theta_k)+B_{ik}\cos(\theta_i-\theta_k)]\ (28)$$

where,G_{ik} is the conductance and the susceptance $B_{ik}$are between bus *i* and *j* respectively.

IV. IMPLEMENTATION OF GA TO FIND THE OPTIMAL PLACE FOR FACTS DEVICES

A. *Review of GA*

Genetic Algorithm is introduced by John Holland in the year of 1970 at University of Michiganin the United States.It generates solution to the optimization problems using the natural solution such as inheritance, mutation, selection and cross over. It is being applied to a wide range of optimization problems in many domains.There are three genetic operators: Selection, Crossover and Mutation [17].

1) *Selection*

Selection method plays an important role in GA. The fitter individuals are selected for the production of offspring to the next generation during the evaluation. The parents who are having the highest fitness value go to the next generation for reproduction. There are so many selection methods are available in GA, in that the tournament selection method is used in this work.

2) *Crossover*

Crossover is the swapping of genes on a chromosome between two parents to produce two types of offspring: The chromosomes of the two parents are copied or randomly recombined to form offspring. After the reproduction, the crossover takes place. Generally, the probability of crossover is in the range of 0.5 and 0.9. It is also known as recombination.

3) *Mutation*

Mutation is the particular gene on a chromosome for a child is changed randomly. This function will be performed only after the crossover takes place. Generally, the probability of mutation is in the range of 0.01 and 0.3. Mutation is needed because sometimes the reproduction and crossover operation may lose some genetic material.

4) *Convergence condition or criterion*

The iterations are continued until a maximum generation is reached or all generated chromosomes are equal or by manual inspection or highest ranking solution's fitness has reached so that succeeding iterations no longer produces better results. Due to the randomness of the GA, the solution may differ for the same initial population. For this reason, the GA runs so many times to get a more acceptable solution.

5) *Representation of chromosomes*

Implementation of GA for a problem starts with the problem representation i.e., parameter encoding. Each individual in the population represents a candidate solution and the element of that solution consists of all the decision variables in the system. The size of the string depends on the precision of the solution required. The initial population size is assigned here as 10 chromosomes.

6) *Fitness function*

After the initialization of chromosomes, the fitness function is evaluated at each step. While evaluating the fitness value, the limits of each constraint are checked. The highest fitness value is finally selected for the next generation. The fitness function can be written as

$$Fit=\max(L_j)+\min(Losses)+\min(PI)+\min(fuelcost)+\min(CG) \quad (29)$$

7) *Genetic operators*

Initial population is then applied with genetic operators like selection, crossover and mutation. In this work, stochastic universal sampling is used to select the fittest parent to produce the offspring in the next generation. Uniform crossover is employed with the probability of 0.9. The offspring's have the properties of both parents.

The mutation is performed after the crossover operation by changing 0 to 1 or vice versa. The particular gene of a chromosome is changed randomly to create the offspring with the different characteristics. It maintains the divergence and the probability of mutation is always smaller than the crossover probability. In this work, the probability of mutation is 0.1. The GA cycle continues until the maximum number of generations has achieved as shown in Fig.4.

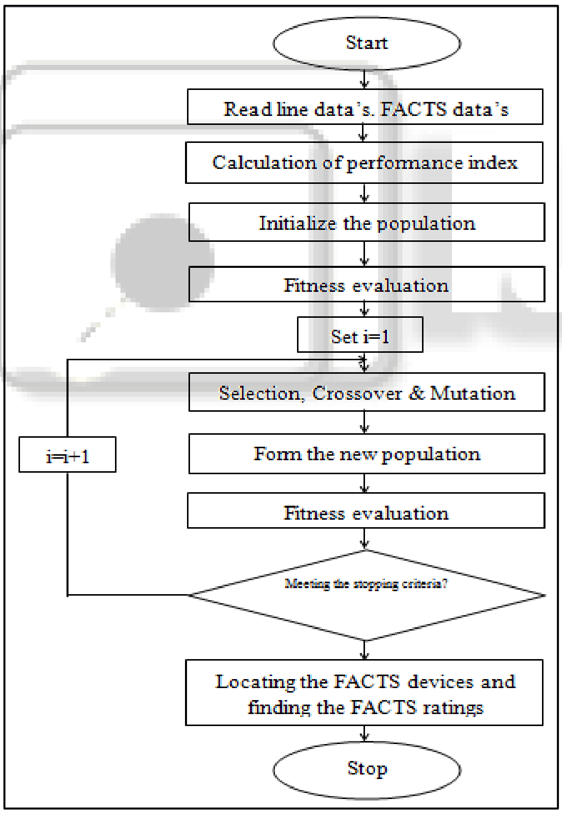


Fig. 4: Flowchart of congestion management using GA

V. RESULTS AND DISCUSSIONS

The effectiveness of the proposed methodology is illustrated using the IEEE 30 bus test system as in Fig.5. It consists of 30 buses, 6 generators, 41 transmission lines, 21 loads, 4 transformers and 2 shunt capacitors. The upper and lower voltage limits at all the bus bars were taken as 1.1p.u and 0.9p.urespectively.

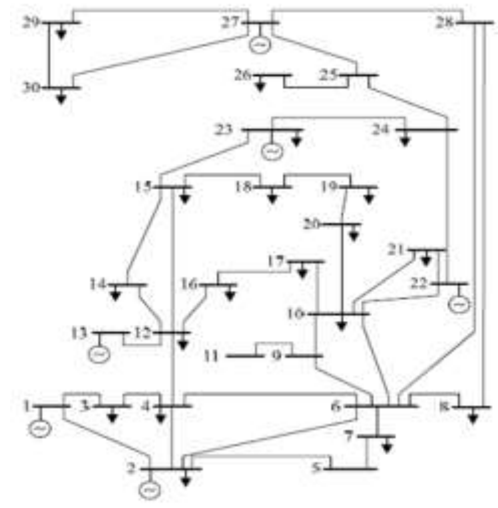


Fig. 5: One line diagram of IEEE 30 bus test system

In this method all possible branch contingencies are considered and as a preliminary computation, the contingency analysis was carried out first. According to these results, the most severe contingencies were the outages of lines [(1–2), (2-5), (1–3), (3–4), (4-6) and (10-20)].

S. No	Outaged line	Overloaded line	Line flow	Line flow limit (MVA)	PI
1	1-2	1-3 3-4 4-6	192.5338 180.7103 112.8335	130 130 90	11.395
2	2-5	2-6 5-7	76.9094 75.1970	65 70	6.002
3	1-3	1-2 2-6	181.387166.7403	130 65	5.827
4	3-4	1-2 2-6	178.6370 65.8125	130 65	5.108
5	4-6	1-2 2-6	134.0622 71.7327	130 65	4.563
6	10-20	15-18	16.3156	16	2.080

Table 1: Line Outage Ranking Using Performance Index

Calculation of performance indices was carried out to identify the suitable locations of the TCSC and SVC to alleviate the line overload. In general, the larger PI value a branch has, the more sensitive it will be. The TCSC and SVCare located in the line 1-2. The convergence characteristic of this genetic algorithm program at the base case level is shown in Fig.6.

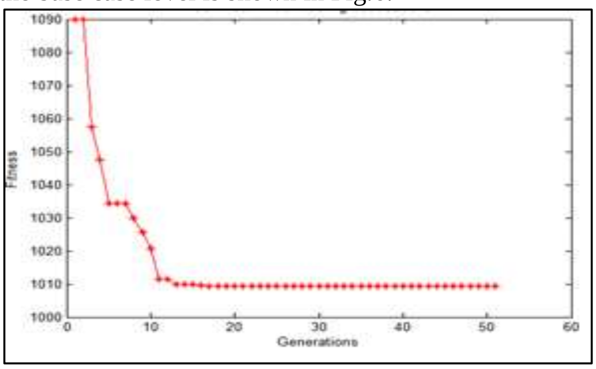


Fig. 6: Convergence characteristics at the base case (Before FACTS)

The GA based OPF algorithm was applied to alleviate the line overload in a severe contingency state. The convergence characteristic for the FACTS ratings is shown inFig.7.Optimal ratings of TCSC and SVC using GA:

TCSC rating is: 0.2000 and

SVC rating is: 60.6327

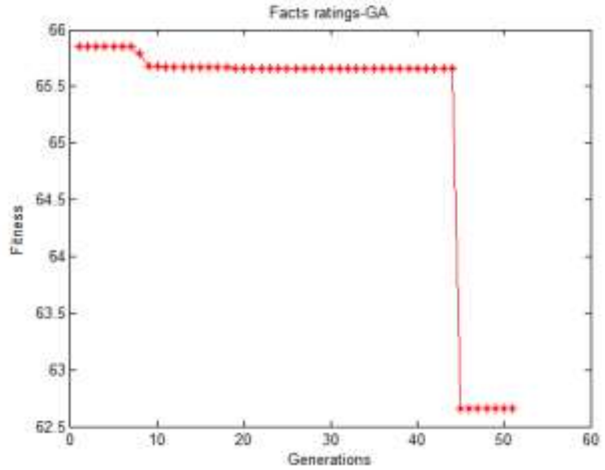


Fig. 7: Convergence characteristics for the FACTS ratings using GA

After fitting the FACTS devices in the most congested lines based on the performance index value, the PI values are reduced as shown in Fig.8.

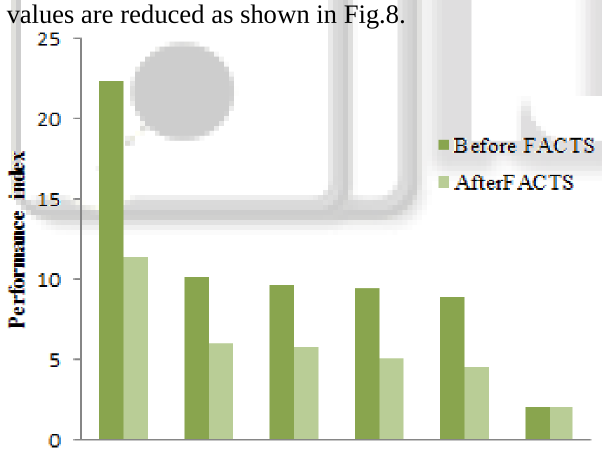


Fig. 8: Comparison of PI

Then, the generators are rescheduled and the convergence characteristics for the generator rescheduling with FACTS is achieved by using the optimization technique as shown in Fig.9.

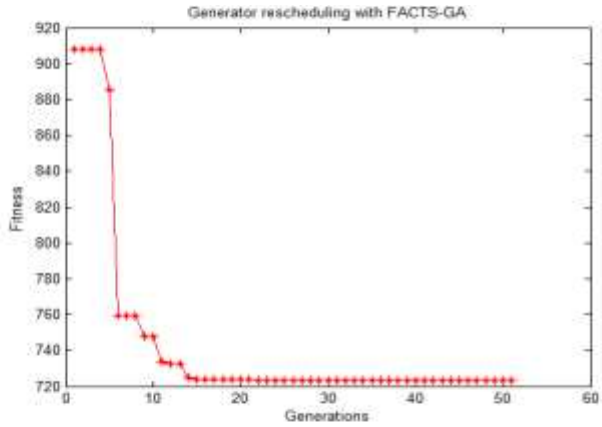


Fig. 9: Convergence characteristics for generator rescheduling with FACTS using GA

The comparison of generated power before and after installing the FACTS devices are shown in Fig.10.

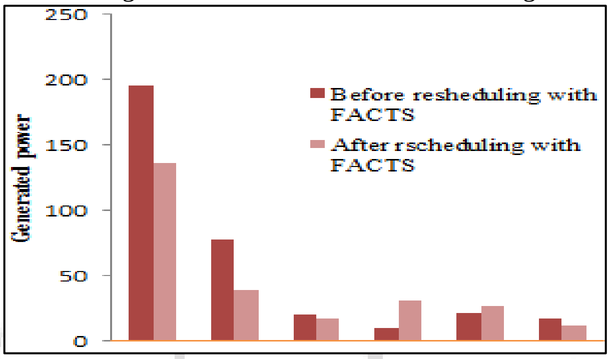


Fig. 10: Comparison of generated power

The generator's minimum and maximum real power limits & the generator's up and down bidding values for all the six generators for IEEE 30 bus system are given in Table II. These values are used in the GA program to calculate the congestion cost.

Gen. No	P_g^{min}	P_g^{max}	**Bid submitted by GENCOs ($/MWhr)**	
			C_{gi}	C_{gd}
1	50	200	22	18
2	20	80	21	19
5	15	50	42	38
8	10	35	43	37
11	10	30	43	35
13	12	40	41	39

Table 2: Generator Power Limits and Bid Data For Ieee 30 Bus System

The proposed algorithm gave a congestion cost of 393.708$/MWhr& the TCSC cost and SVC cost are 143.527($/kVar) and 122.932($/kVar) respectively. Totally the FACTS cost is 266.459($/kVar).

	BVSI	**Losses (Mw)**	**Generation cost ($/Mwhr)**
Before FACTS	23.561	13.296	1009.2
After FACTS	23.559	11.441	723.4918

Table 3: Comparision of BVSI, Losses and Generation Cost

The algorithm was run for a maximum of 50 generations. The best results of the GA were obtained with the following control parameters:

- No. of generations: 50
- Population size: 10
- Crossover probability: 0.9
- Mutation Probability: 0.1

VI. Conclusion

The optimal congestion management approach based on GA is proficiently, minimizing the objective functions of this work. The problem of congestion is modeled as an optimization problem and solved by genetic algorithm optimization technique. This paper presents a GA approach to find the location and ratings of TCSC and SVC which can be used to enhance the security margin for overloaded lines. In this paper, optimal locations are identified using an index named as performance index. From the simulation results, it is clear that, the line overloads are alleviated for severe contingencies. IEEE 30bus test system is used to evaluate the performance of the proposed approach. The effectiveness of the proposed procedure is confirmed by the numerical results.

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