Optimal Choice and Allocation of FACTS Devices in Deregulated Electricity Market using Genetic Algorithms

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***Abstract*--This paper deals with the optimal choice and allocation of FACTS devices in multi-machine power systems using genetic algorithm. The objective is to achieve the power system economic generation allocation and dispatch in deregulated electricity market. Using the proposed method, the locations of the FACTS devices, their types and ratings are optimized simultaneously. Different kinds of FACTS devices are simulated in this study: UPFC, TCSC, TCPST, and SVC. Furthermore, their investment costs are also considered. Simulation results validate the capability of this new approach in minimizing the overall system cost function, which includes the investment costs of the FACTS devices and the bid offers of the market participants. The proposed algorithm is an effective and practical method for the choice and allocation of suitable FACTS devices in deregulated electricity market environment.**

***Index Terms*--Allocation, Bid curve, Consumer, Cost function, Economic generation, FACTS, Genetic algorithms, Investment, Market participant, Optimal power flow, Supplier.**

I. INTRODUCTION

IN recent years, with the deregulation of the electricity market, the traditional concepts and practices of power systems have changed. Better utilization of the existing power system to increase power transfer capability by installing FACTS (Flexible AC Transmission Systems) devices becomes imperative [1, 10].

The parameter and variables of the transmission line, i.e. line impedance, terminal voltages, and voltage angles can be controlled by FACTS devices in a fast and effective way [10,12]. The benefit brought about by FACTS includes improvement of system dynamic behavior and thus enhancement of system reliability. However, their main function is to control power flows [2,4] . Provided that they are placed at optimal locations, FACTS devices are capable of increasing the system loadability too [1]. These aspects are playing an increasingly significant role in the operation and control of the deregulated electricity market.

Many researches were made on the optimal allocation of FACTS devices [1-3]. However, the investment cost of FACTS and their impact on bid curves of the market participants (suppliers and consumers) in liberalized electricity market are not wholly considered [8].

The objective of this paper is to develop an algorithm to find the best locations for the FACTS devices. By means of FACTS optimal placement, the overall cost function, which includes the investment costs of FACTS and the bid offers of the market participants, is minimized.

Different kinds of FACTS devices and their different locations have varying advantages. In realizing the proposed objective, the suitable types of FACTS devices, their location and their ratings must be determined simultaneously. This combinatorial analysis problem is solved using genetic algorithm [1,8,11].

This paper is organized as follows: Following the introduction, different FACTS models are described in section II. Then in section III, the genetic algorithm for the optimal location of FACTS devices is discussed in detail. The simulation results are given in section IV. Finally, brief conclusions are deduced.

II. FACTS MODELS

A. FACTS Devices

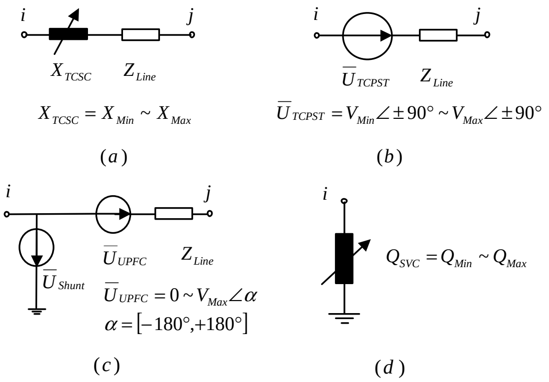

Fig. 1. Block diagram of the considered FACTS devices
(a) TCSC (b) TCPST (c) UPFC (d) SVC

In this paper, four typical FACTS devices have been

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selected: TCSC (Thyristor Controlled Series Capacitor), TCPST (Thyristor Controlled Phase Shifting Transformer), UPFC (Unified Power Flow Controller) and SVC (Static Var Compensator). Their block diagrams are given in Fig. 1.

As shown in Fig. 1, the reactance of the line can be changed by TCSC. TCPST varies the phase angle between the two terminal voltages and SVC can be used to control the reactive compensation. The UPFC is the most powerful and versatile FACTS device due to the fact that the line impedance, terminal voltages, and the voltage angle can be controlled by one and the same device [12].

The power flow P_{ij} through the transmission line ***i-j*** is a function of the line reactance X_{ij}, the voltage magnitude V_j , V_j and the phase angle between the sending and receiving end voltages $\delta_i - \delta_j$.

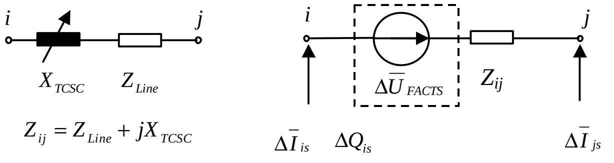
$$P_{ij} = \frac{V_i V_j}{X_{ij}} \left(\delta_i - \delta_j \right) \tag{1}$$

The above-mentioned FACTS devices can be used to control the power flow by changing the transmission line parameters so that the power flow can be optimized. Therefore, in multi-machine power systems, optimal utilization of generation units can be achieved by means of FACTS devices.

B. Mathematical Models of FACTS Devices

In this paper, the mathematical models of the FACTS devices are developed mainly to perform the steady-state analysis. Therefore the TCSC is modeled to modify the reactance of the transmission line directly. SVC, TCPST and UPFC are modeled using the power/current injection method [4]. Furthermore, for the TCSC, TCPST and UPFC, their mathematical model is integrated into the model of the transmission line, whereas the SVC model is only incorporated into the sending-end as a shunt element of the transmission line.

The mathematical models of FACTS, as shown in Fig. 2, are implemented in *Matpower 2.0* [9].



(a) (b)

Fig. 2. Mathematical models of the FACTS devices.
(a) TCSC. (b) TCPST, UPFC and SVC.

TCSC

By modifying the reactance of the transmission line, the TCSC acts as the capacitive or inductive compensation respectively. In this study, the reactance of the transmission line is adjusted by TCSC directly. The rating of TCSC is depend on the reactance of the transmission line where the TCSC is located:

$$X_{ij} = X_{Line} + X_{TCSC}, \quad X_{TCSC} = rt\csc \cdot X_{Line} \tag{2}$$

where X_{Line} is the reactance of the transmission line and *rtcsc* is the coefficient which represents the degree of compensation by TCSC.

To avoid overcompensation, the working range of the TCSC is chosen between $-0.7X_{Line}$ and 0.2 X_{Line} [1,2].

$$rt\csc_{\min} = -0.7, \quad rt\csc_{\max} = 0.2$$

TCPST

The voltage angle between the sending and receiving end of the transmission line can be regulated by TCPST. It is modeled as a series compensation voltage $\Delta \overline{U}_{FACTS} = \Delta \overline{U}_{TCPST}$, as shown in Fig 2. (b), which is perpendicular to the bus voltage. The working range of the TCPST is between -5 degrees to +5 degrees. The injected currents at bus *i* and bus *j* can be expressed as follows:

$$\Delta \overline{I}_{is} = \frac{\Delta \overline{U}_{TCPST}}{Z_{ij}}, \quad \Delta \overline{I}_{js} = -\frac{\Delta \overline{U}_{TCPST}}{Z_{ij}} \tag{3}$$

SVC

The SVC can be operated as both inductive and capacitive compensation. It is modeled as an ideal reactive power injection at bus *i*, as shown in Fig. 2 (b). The injected power at bus *i* is:

$$\Delta Q_{is} = Q_{SVC} \tag{4}$$

UPFC

Basically, the UPFC has two voltage source inverters (VSI) sharing a common dc storage capacitor. It is connected to the system through two coupling transformers [6,7,12]. In this study, the series compensation $\Delta \overline{U}_{FACTS} = \Delta \overline{U}_{UPFC}$ is employed. The injected currents at bus *i* and bus *j* can be expressed as follows:

$$\Delta \overline{I}_{is} = \frac{\Delta \overline{U}_{UPFC}}{Z_{ij}}, \quad \Delta \overline{I}_{js} = -\frac{\Delta \overline{U}_{UPFC}}{Z_{ij}} \tag{5}$$

III. COST FUNCTIONS

As mentioned above, the main objective of this paper is to find the optimal locations of FACTS devices to minimize the overall cost function consisting of bid offers of the market participants and FACTS devices investment costs.

In this work, a modified version of power simulation software: *Matpower* 2.0 is employed [9]. For the intended research, *Matpower* has been extended by incorporating the mathematical models of FACTS devices. Furthermore, cost functions are incorporated for:

- Bids of suppliers and consumers.
- Investment costs of FACTS devices.

A. Bids of the Suppliers and Consumers in Pool Market

Pool market is a basic type of the deregulated power markets. Electricity pools are market institutions designed to permit trade and competition in the supply of energy whilst simultaneously allowing the overall control and coordination of generation and transmission.

The main characteristic of electricity pool market is that the power is traded through the market and not bilaterally between producers and consumers. The market is operated either by a separate *Pool Operator* or directly by the *Independent System Operator* (ISO). The task of market operator is to lead the pool market to a short-run economic optimum.

In order to achieve this aim, the market operator collects the electric power bids from suppliers as well as from consumers. Then the market operator runs an OPF program taking into consideration the network constraints. The objective of this OPF is to minimize the total costs also known as social welfare [13].

In this paper, the uncovered load of the consumers are modeled as a fictitious generator [13]. In electricity market, the uncovered load always occurs when the congestion arises. Therefore, the bid function for the supplier and consumer can be formulated as follows:

$$c_2(\mathbf{P}_G) = \mathbf{p}_{\min}^T \mathbf{P}_G \qquad (6)$$

where $\mathbf{P}_G$ is a vector of the generation power, which includes the generation power of the suppliers and the fictitious generation power of the consumers [13]. $\mathbf{p}_{\min}$ is a vector of minimum acceptable price (bid) from all the generators.

B. *FACTS Devices Cost Functions*

According to [8], the cost functions for SVC, TCSC and UPFC are developed as follows:

UPFC:

$$c_{1UPFC} = 0.0003s^2 - 0.2691s + 188.22 (US\$/kVar) \qquad (7)$$

TCSC:

$$c_{1TCSC} = 0.0015s^2 - 0.7130s + 153.75 (US\$/kVar) \qquad (8)$$

SVC:

$$c_{1SVC} = 0.0003s^2 - 0.3051s + 127.38 (US\$/kVar) \qquad (9)$$

where c_{1UPFC}, c_{1TCSC} and c_{1SVC} are in *US$/kVar* and s is the operating range of the FACTS devices in *MVar*.

The cost function for SVC, TCSC and UPFC are shown in Fig. 3.

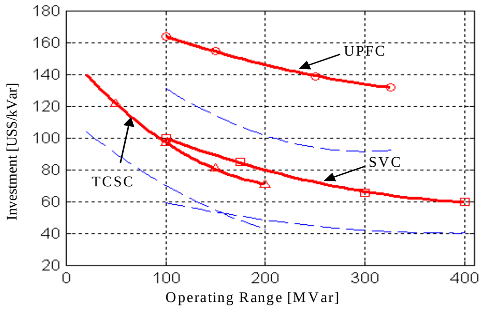


Fig. 3. Cost functions of the FACTS devices: SVC, TCSC and UPFC.
——: Upper limit: Total investment costs
------: Lower limit: Equipment costs
—o—: UPFC. —Δ—: TCSC. —□—: SVC.

The cost of a TCPST is more related to the operating voltage and the current rating of the circuit concerned [2,3,5]. Thus, once the TCPST is installed, the cost is fixed and the cost function can be expressed as follows [5]:

$$C_{TCPST} = d \cdot P_{\max} + IC \ \ (US\$) \qquad (10)$$

where d is a positive constant representing the capital cost and IC is the installation costs of the TCPST. P_{max} is the thermal limit of the transmission line where TCPST is to be installed [5].

IV. OPTIMAL FACTS ALLOCATION

The formulation of the optimal allocation of FACTS devices can be expressed as follows [5]:

$$\begin{aligned} \min. \quad & c_{\text{Total}} = c_1(\mathbf{f}) + c_2(\mathbf{P}_G) \\ s.t. \quad & \mathbf{E}(\mathbf{f},\mathbf{g}) = 0 \\ & \mathbf{B}_1(\mathbf{f}) < \mathbf{b}_1, \ \ \mathbf{B}_2(\mathbf{g}) < \mathbf{b}_2 \end{aligned} \qquad (11)$$

where,

$c_1(\mathbf{f})$ is the average investment costs of FACTS devices.

$c_2(\mathbf{P}_G)$ is the bid offers of the market participants.

c_{Total} is the overall cost of objective function $c_1(\mathbf{f}) + c_2(\mathbf{P}_G)$.

$\mathbf{E}(\mathbf{f},\mathbf{g})$ represents the equality constraints with respect to active and reactive power balance.

$\mathbf{B}_1(\mathbf{f})$ and $\mathbf{B}_2(\mathbf{g})$ are the inequality constrains for FACTS devices and the conventional power flow respectively.

$\mathbf{f}$ and $\mathbf{P}_G$ are vectors that represent the variables of FACTS devices and the generation power of the generators and fictitious generators.

$\mathbf{g}$ represents the operating state of the power system (parameters provided for the optimal power flow).

The unit for generation cost is *US$/Hour* and for the investment costs of FACTS devices are *US$*. They must be unified into *US$/Hour*. Normally, the FACTS devices will be in-service for many years [10,12]. However, only a part of its lifetime is employed to regulate the power flow. In this paper, five years is applied to evaluate the cost function. Therefore the average value of the investment costs are calculated using the following equation:

$$c_1(\mathbf{f}) = \frac{c(\mathbf{f})}{8760 \times 5} \ \ (US\$/Hour) \qquad (12)$$

where $c(\mathbf{f})$ is the total investment costs of FACTS devices.

As mentioned above, power system parameters can be changed using FACTS devices. These different parameters produce different results on the objective function (11). Also, the variation of FACTS locations and FACTS types has also influence on the objective function. Therefore, using the conventional optimization methods is not easy to find the optimal location of FACTS devices, their types and their ratings simultaneously. To solve this problem, the genetic algorithm is employed.

V. GENETIC ALGORITHMS

Based on the mechanisms of natural selection and genetics, GAs (genetic algorithms) are global search techniques. They can search several possible solutions simultaneously and they do not require any prior knowledge or special properties of the objective function [1,8,11]. Moreover, they always produce high quality solutions, and therefore, they are excellent methods for searching optimal solution in a complex problem. Additionally, GAs are practical algorithm and easy to be implemented in the power system analysis.

The GAs start with random generation of initial population and then the selection, crossover and mutation are proceeded until the maximal generation is reached.

A. Encoding

The objective is to find the optimal locations for the FACTS devices within the equality and inequality constrains. Therefore, the configuration of FACTS devices is encoded by three parameters: the location, type and rating [1]. Each individual is represented by n_{FACTS} number of strings, where n_{FACTS} is the number of FACTS devices needed to be analyzed in the power system, as shown in Fig. 4.

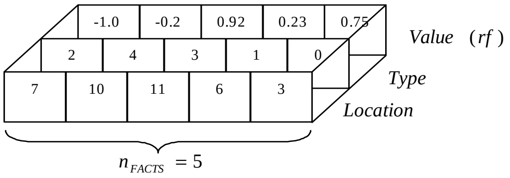


Fig. 4. Individual configuration of FACTS devices.

The first value of each string corresponds to the location information. It is the number of the transmission line where the FACTS is to be located. Each string has a different value of location [1]. In other words, it must be ensured that on one transmission line there is only one FACTS device. Moreover, SVC is installed only at one node of the transmission line and the sending node is selected in this study.

The second value represents the types of FACTS devices [1]. The values assigned to FACTS devices are: "1" for TCSC; "2" for TCPST; "3" for UPFC and "4" for SVC. Particularly, if there is no FACTS device needed on the transmission line, the value 0 will be employed.

The last value rf represents the rating of each FACTS device. This value varies continuously between –1 and +1. The real value of each FACTS device is then converted according to the different FACTS model under the following criterion:

TCSC:

TCSC has a working range between $-0.7X_{Line}$ and $0.2X_{Line}$ [2,3]. The X_{Line} is the reactance of the transmission line where the TCSC to be installed. Therefore rf is converted into the real degree of compensation *rtcsc* using the following equation:

$$rtcsc = rf \times 0.45 - 0.25 \tag{13}$$

UPFC:

The inserted voltage of UPFC ΔU_{UPFC} has a maximum magnitude of $0.1V_m$, where V_m is the rated voltage of the transmission line where the UPFC is installed. The angle of ΔU_{UPFC} can be varied from $-180°$ to $180°$. Therefore rf is converted into the working angle *rupfc* using the following equation:

$$rupfc = rf \times 180 \ (degrees) \tag{14}$$

TCPST:

The working range of TCPST is between $-5°$ and $5°$. Then rf is converted into the real phase shift value *rtcpst* using the following equation:

$$rtcpst = rf \times 5 \ (degrees) \tag{15}$$

SVC:

The working range of SVC is between –100MVar and 100MVar. Then rf is converted into the real compensation value using:

$$rsvc = rf \times 100 \ (MVar) \tag{16}$$

B. Initial Population

The initial population is generated from the following parameters [1]:

n_{FACTS}:	the number of FACTS devices to be simulated.
n_{Type}:	FACTS types.
$n_{Location}$:	the possible locations for FACTS devices.
n_{Ind}:	the number of individuals of the population.

First, as shown in Fig. 5, a set of n_{FACTS} numbers of strings are produced. For each string, the first value is randomly chosen from the possible locations $n_{Location}$.

The second value, which represents the types of FACTS devices, is obtained by randomly drawing numbers among the selected devices [1]. Particularly, after the optimization, if there is no FACTS device necessary for this transmission line, the second value will be set to zero.

The third value of each string, which contains the ratings of the FACTS devices, are randomly selected between –1 and +1.

To obtain the entire initial population, the above operations are repeated n_{Ind} times [1]. Fig. 5 shows the calculation of the entire population.

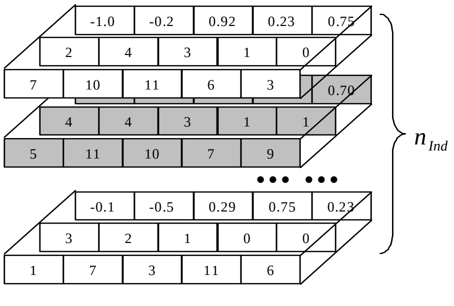


Fig. 5. Calculation of the entire population.

C. Fitness Calculation

After encoding, the objective function (fitness) will be evaluated for each individual of the population. The fitness is a measure of quality, which is used to compare different solutions [1, 11]. In this work, the fitness is defined as follows:

$$Fitness = m - c_{Total} \tag{17}$$

Because the GAs can only find the maximum positive value of the objective function, a large positive constant *m* is selected to convert the objective function into a maximum one. In this paper, *m* is selected as 4000 *US$/hour*.

Then reproduction, crossover and mutation are applied successively to generate the offspring.

D. Reproduction

Reproduction is a process where the individual is selected to move to a new generation according to its fitness. The biased roulette wheel selection [1] is employed. The probability of an individual's reproduction is proportional to its part on the biased roulette wheel [11].

E. Crossover

The main objective of crossover is to reorganize the information of two different individuals and produce a new one [1,11].

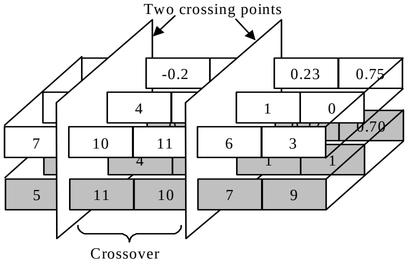


Fig. 6. Two points crossover.

A two-points crossover [1] is applied and the probability *pc* of the crossover is selected as 0.95. First, two crossing points are selected uniformly at random along the individuals. Elements outside these two points are kept to be part of the offspring. Then, from the first position of crossover to the second one, elements of the three strings of both parents are exchanged [1,11].

F. Mutation

Mutation is used to introduce some sort of artificial diversification in the population to avoid premature convergence to local optimum [4,11]. Non-uniform mutation, which has proved to be successful in a number of studies [11], is employed in this paper.

For a given parent $X = x_1 \, x_2 \ldots x_k \ldots x_l$, if the gene x_k is selected for mutation and the range of x_k is $\left[U^k_{Min}, U^k_{Max}\right]$, then the result x_k' is:

$$x_k' = \begin{cases} x_k + \Delta\left(t, U^k_{Max} - x_k\right) & if \quad random(0,1) = 0 \\ x_k - \Delta\left(t, x_k - U^k_{Min}\right) & if \quad random(0,1) = 1 \end{cases} \tag{18}$$

where

$$\Delta(t,y) = y \cdot \left(1 - r^{\left(1 - \frac{t}{T}\right) \cdot b}\right) \tag{19}$$

$\Delta(t,y)$ (y represents $x_k - U^k_{Min}$ and $U^k_{Min} - x_k$) returns a value in the range [*0,y*]. Its probability being close to 0 and increases as *t* increases (*t* is generation number). This property enables the operator to search the space uniformly initially (when *t* is small), and very locally at later stages [11]. In (19), *r* is a random value in the range of [*0,1*] and *b* is a parameter determining the degree of non-uniformity. In this simulation, *b*=2 is used.

The above-mentioned operations of selection, crossover and mutation are repeated until the maximal generation is achieved.

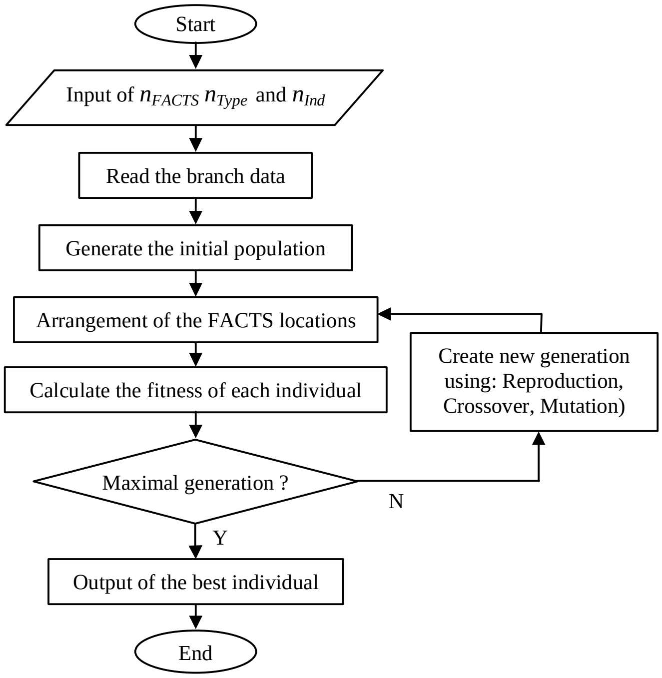


Fig. 7. Flow chart of the GA optimization.

The proposed optimization strategy is summarized in Fig. 7. In order to ensure that there is only one FACTS device on each transmission line, the process of "Arrangement of the FACTS locations" is necessary [1].

VI. CASE STUDY

In order to verify the effectiveness of the proposed method, the 10-bus test system, as illustrated in Fig 8, is simulated. The detailed information about this test system and the bid offers of the market participants are given in Appendix A and B. Different operating conditions are simulated for the determination of the optimal FACTS locations.

The initial value of n_{FACTS}, which indicates the number of FACTS devices to be simulated, is defined as five. The total number of generation is 200 and there are 20 individuals in each generation. Simulation results of two typical cases are presented in this section.

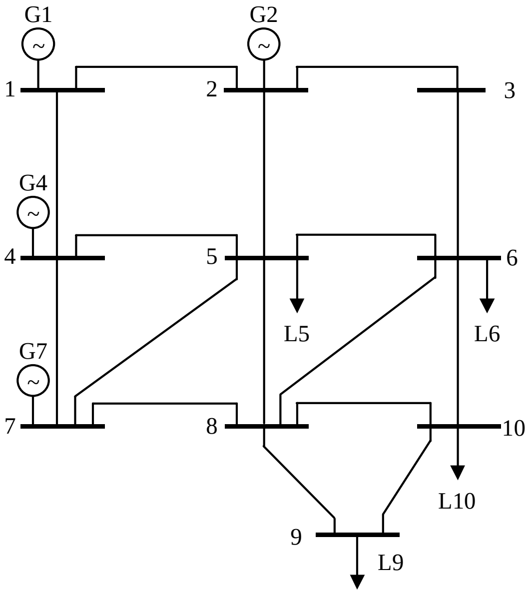


Fig. 8. 10-bus test system

A. Case 1: Power flow congestion

In this case, by modifying the maximum transmission capacity of the corresponding transmission lines, the power flow congestion is introduced into transmission lines 1-2, 2-5, 4-5, 5-8 and 7-8. The total generation cost, which includes the generation costs of the real and fictitious generators, is 789.08 *US$/hour*. As can be seen from Table I, the most severe congestion is on the line 4-5. Where μ_{Sf} and μ_{St} are Lagrange multipliers of the sending and receiving end with respect to inequality constraints of the power flow. S_{Limit} is the maximum transfer capability of the transmission line.

TABLE I
RESULT OF THE ACTIVE POWER FLOW CONGESTION FOR CASE 1

Line	μ_{Sf}	μ_{St}	S_{Limit} (MW)
1-2	0.026	-	100.00
2-5	-	0.051	120.00
4-5	9.599	8.965	70.00
5-8	0.861	-	65.00
7-8	0.300	-	94.00

After the GA optimization, FACTS device is not necessary for this case. It is obvious that FACTS will alleviate the power flow congestion. However, in comparison with the FACTS costs and its total benefit for the overall generation cost, FACTS device will not lead to a cost reduction in this situation.

B. Case 2: Power flow congestion

In this case, by modifying the maximal transmission capacity of the corresponding transmission line, the power flow congestion is located at the transmission line 1-2, 4-5, 5-8 and 7-8. The total generation cost is 1117.75 *US$/hour*. As can be seen from Table II, the most severe congestion is also on the line 4-5.

TABLE II
RESULT OF THE ACTIVE POWER FLOW CONGESTION FOR CASE 2

Line	μ_{Sf}	μ_{St}	S_{Limit} (MW)
1-2	0.013	-	100.00
4-5	45.198	42.774	55.00
5-8	4.552	-	65.00
7-8	1.662	-	94.00

After the GA optimization, a TCSC on the transmission line 4-5 with a compensation level of –70% X_{Line} is necessary. The simulation result is shown in Fig. 9. The overall system cost, which includes the total generation costs and FACTS investment costs, is 915.90 *US$/hour*.

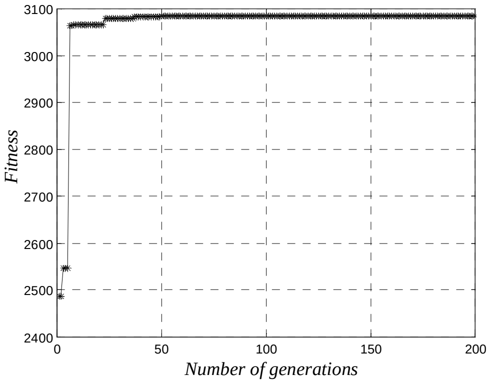


Fig. 9. Simulation result

In this case, due to the higher total generation cost, the FACTS devices is necessary for the congestion management. Simulation result shows that for the considered power system, the TCSC is the most efficient solution. Even though UPFC is the most powerful FACTS device, it has not been applied due to its extremely high investment cost.

C. Practical application

Simultaneous optimization of the locations of the FACTS devices, their types and ratings is a very complicated optimization problem in large power systems. The proposed algorithm is suitable to search several possible solutions simultaneously. It always produces high quality solutions and it is faster than the traditional optimization methods in large power system researches. Furthermore, this algorithm is practical and easy to be implemented into the large power system analysis.

VII. CONCLUSIONS

In this paper, a genetic algorithm based approach is proposed to determine the suitable type of FACTS devices and its optimal location in deregulated electricity market. Four typical FACTS devices, i.e. TCSC, UPFC, TCPST and SVC, are simulated. The overall system cost function, which includes the bid offers of the market participants (suppliers and consumers) and the investment costs of FACTS devices, is employed to evaluate the power system performance.

Simulation results validate the efficiency of this new approach in minimizing the overall system cost function. Furthermore, the locations of the FACTS devices, their types and ratings are optimized simultaneously. The proposed algorithm is an effective and practical method for the allocation of FACTS devices in deregulated electricity market.

VIII. ACKNOWLEDGMENT

The authors would like to thank Dr.-Ing. Fekadu Shewarega for his valuable suggestions and comments.

IX. APPENDICES

A. Detailed information about the 10-bus test system

TABLE AI

DATA OF THE 10-BUS TEST SYSTEM

(S_b=100 *MVA*, V_b=380 *kV*)

From bus	**To bus**	*R* **[*p.u.*]**	*X* **[*p.u.*]**	*b* **[*p.u.*]**	**Transfer capacity [*MVA*]**
1	2	0.0034	0.0360	1.2696	100
1	4	0.0034	0.0360	1.2696	110
2	3	0.0034	0.0360	1.2696	120
2	5	0.0034	0.0360	1.2696	120
3	6	0.0034	0.0360	1.2696	150
4	5	0.0034	0.0360	1.2696	70
4	7	0.0028	0.0288	1.0156	100
5	6	0.0028	0.0288	1.0156	85
5	7	0.0034	0.0360	1.2696	70
5	8	0.0017	0.0180	0.6348	65
6	10	0.0024	0.0252	0.8888	85
6	8	0.0034	0.0360	1.2696	80
7	8	0.0017	0.0180	0.6348	94
8	9	0.0017	0.0180	0.6348	155
8	10	0.0028	0.0288	1.0156	115
9	10	0.0024	0.0252	0.8888	50

B. Generation Cost Function

TABLE AII

BID OFFERS OF MARKET PARTICIPANTS

Bus	**Art**	P_{max} [*MW*]	p_{max} [*ct/kWh*]
1	Supplier	150	3
2	Supplier	150	6
4	Supplier	150	6
7	Supplier	250	9
5	Consumer	100	20
6	Consumer	100	20
9	Consumer	100	20
10	Consumer	100	20

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