Impact of FACTS Devices on Bilateral Transactions of Deregulated Power System

I. Catherine Divya
PG Scholar
Electrical and Electronics Engineering
Kamaraj College of Engineering and Technology
Virudhunagar, Tamilnadu, India

Dr. S. Nagalakshmi
Assistant Professor
Electrical and Electronics Engineering
Kamaraj College of Engineering and Technology
Virudhunagar, Tamilnadu, India

***Abstract*—This paper concerns the optimal location and control of Flexible AC Transmission System (FACTS) devices using Differential Evolution (DE) for achieving Security Constrained Optimal Power Flow (SCOPF) for Bilateral model of deregulated electricity market. This approach uses AC load flow equations with the constraints on power system generation, transmission line flow, magnitude of bus voltages, and FACTS device settings. For the proposed method two types of FACTS devices namely, Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC) are used. The bilateral transactions are modeled using secured bilateral transaction matrix utilizing the AC distribution factor with slack bus contribution.In this work, SCOPF is performed considering the installation cost of FACTS devices during normal operating condition. To validate the proposed approach simulations are performed on IEEE 6 bus system. The impact of FACTS devices on bilateral transactions of the deregulated power system is analysed based on the economical aspect as well as security aspect. The results indicate that by optimal location and control of FACTS devices is determined by DE algorithm reduces the active power generation bidding cost as well as the installation of FACTS devices. Among the two FACTS devices, SVC gives minimum cost of active power generation bidding and minimum installation cost than TCSC.**

Keywords*— Differential Evolution(DE) algorithm, Flexible Alternating Current Transmission System (FACTS), Security Constrained Optimal Power Flow (SCOPF), Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC).

I. INTRODUCTION

In recent years, rapid growth of power demand due to the growing population necessitates the electric utilities to serve more power through their networks and also to maintain system security [1]. Due to the increased demand electric power system is changing into Deregulated Structure. In general, deregulated power system consists of three models namely pool, bilateral and hybrid [2]. In this paper, SCOPF is considered in bilateral model of deregulated power system. In the bilateral model, the bilateral transactions take place directly between the buying and selling entities.Basics about bilateral transactions are studied, under a deregulated environment, electricity consumers and suppliers will be permitted to establish various bilateral service contracts [3]. The bilateral transactions are modeled using secured bilateral transaction matrix utilizing AC Distribution Factor with slack bus contribution [4, 5]. For pure bilateral model, the reactive power support is obtained from synchronous generators.The operation of power systems under a mix of physical bilateral transactions and pool-supplied demand, all subject to some degree of combined pool/bilateral coordination is examined [6].

Better system operating conditions are achieved when sufficient security and economy are accounted which is known as Security Constrained Optimal Power Flow (SCOPF).The SCOPF is an extension of OPF problem which takes into account constraints arising from the operation of the system under a set of postulated contingencies. The SCOPF problem is a nonlinear, non-convex, large-scale optimization problem, with both continuous and discrete variables [7, 8].

As a solution to this problem, either the existing transmission lines must be effectively utilized, or new transmission lines should be added to the existing system. Environmental right-of-way and cost problems are major hurdles for power transmission network expansion. Hence there is an interest for better utilization of existing power system capabilities. Flexible AC Transmission Systems (FACTS) devices have gained a great interest in transmission system due to recent advances in power electronics [9, 10].

SCOPF with FACTS devices using conventional methods and computational algorithms have been carried out. Sensitivity based approach was proposed to locate Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controller (UPFC), considering voltage and angle sensitivities with respect to changes in the system load [11]. Continuation Power Flow (CPF) was used for obtaining the size and locations of the series compensators to increase the security of the system. This study identifies critical lines that can initiate cascading line outages and optimal location and parameter settings of series and shunt compensators [12]. Population based computational intelligent techniques such as Genetic Algorithm (GA), Evolutionary Programming (EP) and Particle Swarm Optimization (PSO) were used to determine optimal location of FACTS devices. EP was proposed to obtain optimal placement of multi-type FACTS devices for simultaneously maximizing the total transfer capability whereas minimizing the total system real power loss and the results are better when compared to loss sensitivity index method [13]. The optimal location for single and multi-type FACTS devices to improve system security was determined using PSO [14]. Among the available algorithms to solve optimization problems DE is simple, accurate, robust, few parameters to set, and also finds the optimum in almost every run[15].

In this paper, DE is used for finding the optimal location and parameter setting of TCSC and SVC to achieve Secured optimal power flow in bilateral model of deregulated power system. The objective of this work is performed in two steps. The first step is to obtain secured bilateral transaction matrix which has minimum overall deviation from the proposed transaction matrix. Then, the second step is to optimally locate TCSC and SVC to minimize both the active power generation cost and installation cost of FACTS devices satisfying the equality and inequality constraints. In order to validate the performance, simulations are performed on IEEE 6 bus system and the results are analyzed.

II. MODELING OF FACTS DEVICES

A. Modeling of TCSC

TCSC consists of series compensating capacitor shunted by thyristor controlled reactor. It is modeled as a controllable reactance, inserted in series with the transmission line to adjust line impedance and thereby control power flow to increase the network security as shown in Fig.1 [16].

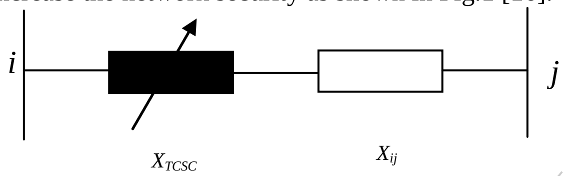

Fig. 1 Block diagram of TCSC

$$X_{ij\,new} = X_{ij} + X_{TCSC} \quad (1)$$

Where, X_{ijnew} - reactance after the location of TCSC
X_{ij} - reactance of the transmission line
X_{TCSC} - reactance of the TCSC

B. Modeling of SVC

SVC is modelled as shunt connected static VAR generator or absorber, Q_{SVC} whose output is adjusted to exchange capacitive or inductive compensation and is inserted directly to the load bus as shown in Fig. 2 [17].

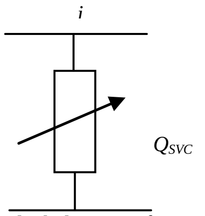

Fig. 2 Block diagram of SVC

III. PROBLEM FORMULATION

A. Objective function

The objective function is to minimize the active power generating cost, which is expressed as:

$$Min\sum_{i\in N_g} C_i(P_{gi}) + IC_{FACTS} \quad (2)$$

Where,

$C_i(P_{gi}) = aP_{gi}^2 + bP_{gi} + c$ - cost curve of i[th] generator;

a,b,c - cost coefficients of the generator.

$$IC_{TCSC} = 0.0015s^2 - 0.7130s + 153.75 \quad (3)$$

$$IC_{SVC} = 0.0003s^2 - 0.3051s + 127.38 \quad (4)$$

Where,

$$s = Q_2 - Q_1 \quad (5)$$

s - Operating range of FACTS devices in MVAR;
Q_2 - Reactive power flow in the line after installing FACTS devices in MVAR;
Q_1 - Reactive power flow in the line before installing FACTS devices in MVAR;

B. Equality Constraints

Power balance equation

$$P_i(V,\delta) + P_{di} - P_{gi} = 0 \qquad i=1\ldots N_b \quad (6)$$

$$Q_i(V,\delta) + Q_{di} - Q_{gi} = 0 \qquad i=1\ldots N_b \quad (7)$$

C. Inequality Constraints

Power generation limit

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \qquad i=1\ldots N_g \quad (8)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \qquad i=1\ldots N_g \quad (9)$$

Bus voltage limits

$$V_i^{min} \le V_i \le V_i^{max} \qquad i=1\ldots N_b \quad (10)$$

Apparent line flow limit

$$S_l \le S_l^{max} \qquad l=1\ldots N_l \quad (11)$$

FACTS device constraints

$$-0.8*X_{ij} \le X_{TCSC} \le 0.2*X_{ij} \quad (12)$$

$$-100 \le Q_{SVC} \le 100 \quad (13)$$

Where,

P_{gi}, Q_{gi} - real and reactive power generation at bus i;
P_{di}, Q_{di} - real and reactive power demand at bus i;
V_i - Voltage magnitude at bus i;
V_i^{min}, V_i^{max} - minimum and maximum voltage limits;
$P_{gi}^{min}, P_{gi}^{max}$ - minimum and maximum limits for real power generation;
N_b - The total number of buses;
N_g - The total number of generator buses;
S_l - The apparent power flow in transmission line;
S_l^{max} - Maximum power flow limit;
X_{ij} - Reactance of the transmission line;
X_{TCSC} - Reactance of the TCSC;

D. Determination of Secured Bilateral Transaction Matrix

The lossless bilateral contract model is formulated using the contracts as controllable variables and the system security limits as binding constraints [9]. There are some intrinsic properties associated with this transaction matrix, namely column, row, range and flow rules [8], [9]. The bilateral transactions between sellers and buyers are deemed to be secured only if the transaction matrix satisfies all the intrinsic properties.

- Bilateral Model of Deregulated Power System

Bilateral model is one in which the customers are free to contract directly with power generating companies to obtain lowest rate and most desirable service. It is also called as direct access model. It is shown in fig.3

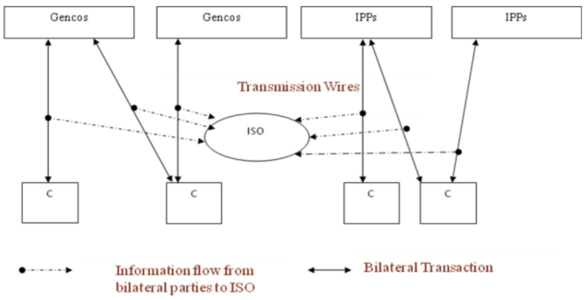

Fig.3. Bilateral Model of Deregulated Power System

- Objective function

The objective is to find secured bilateral transaction matrix T which has overall minimum deviation from the proposed transaction matrix T^0 satisfying equality and inequality constraints.

$$Min \sum_i \sum_j b_{ij} \left| t_{ij} - t_{ij}^{0} \right|^2 \tag{14}$$

where t_{ij}^0- ijth element of proposed transaction matrix T^0, t_{ij} - ijth element of secured bilateral transaction matrix T, b_{ij} - constant assumed to be 1 for all (i,j) terms.

- Equality constraints

Real and reactive power balance equations

$$P_{gi} - P_{di} = P_i \qquad \forall\ j \in n_b \tag{15}$$

$$Q_{gi} - Q_{di} = Q_i \qquad \forall\ j \in n_b \tag{16}$$

Real power generation for bilateral transactions

$$P_{gb_i} = \sum_j t_{ij} \qquad \forall\ j \in n_b \tag{17}$$

Real power demand for bilateral transactions

$$P_{db_j} = \sum_i t_{ij} \qquad \forall\ i \in n_b \tag{18}$$

Real power balance equation for bilateral transactions

$$\sum_i P_{gbi} = \sum_j P_{dbj} \tag{19}$$

Power flow equations for bilateral model

$$P_{fb} = ACDF\left(P_{gb} - P_{db}\right) \tag{20}$$

where

P_{gb} - Bilateral real power generation,

P_{db} - Bilateral real power demand,

ACDF - AC distribution factor,

P_{fb} - Bilateral real power flow.

- AC Distribution Factor

AC Distribution Factor is defined as change in real power flow in transmission line connected between bus-i and bus -j (ΔP_{ij}) due to unit change in power injection at any bus-n (ΔP_n).

$$ACDF_n^{ij} = \frac{\Delta P_{ij}}{\Delta P_n} \tag{21}$$

To obtain fairness in the competitive environment, the line flow sensitivity at the slack bus should not be zero corresponding to the injections at the slack bus. To attain this, a shift factor as defined in [13] has been obtained and added to the calculated values of ACDF. The modified values of ACDF obtained are

$$\left(ACDFs_n^{\ k}\right)^{new} = \left(ACDFs_n^{\ k}\right) + P\_shiftfactor \tag{22}$$

$$P\_shiftfactor = -\frac{1}{2}\left(\frac{\partial P_{ij}}{\partial P_i} + \frac{\partial P_{ij}}{\partial P_j}\right)$$

IV. IMPLEMENTATION OF DE FOR SCOPF WITH FACTS DEVICES

Storn presented classical DE algorithm in 1995 which consists of four steps namely initialization of population, mutation, crossover or recombination and selection [18].

1) Initialization

DE searches for global optimum point in a D-dimensional real parameter space. The population members are randomly initialized using Equation (22).

$$X_{i,j}^{(0)} = X_{j\,min} + rand\,[0,1] * (X_{j\,max} - X_{j\,min}) \qquad i \in [1, Np] \qquad j \in [1, D] \tag{22}$$

Where

Np - population size;

D – dimension;

$X_{i,j}^{(0)}$ - initially generated target vector;

rand [0,1] - uniformly distributed random number between 0 and 1;

i - number of population;

j - number of variables;

X_{jmax} - maximum value of the individual;

X_{jmax} - minimum value of the individual.

Considering the variables that should be optimized (i.e., the location and the parameter setting of FACTS device). These parameters are randomly initialized within feasible ranges.

2) Mutation

Mutation is a change or perturbation with a random element. The difference of any two of these three vectors is scaled by a scaling factor F and the scaled difference is added to the third one to obtain the donor vector using Equation (23).

$$V_{i,j}^{(t)} = X_{r1,j}^{(t)} + F * (X_{r2,j}^{(t)} - X_{r3,j}^{(t)}) \tag{23}$$

3) Crossover

To enhance the potential diversity of population, a crossover operation is performed after generating the donor vector through mutation. The trial vector is determined using Equation (24)

$$U_{i,j}^{(t)} = \begin{cases} V_{i,j}^{(t)} & \text{if } rand(0,1) < Cr \\ X_{i,j}^{(t)} & \text{else} \end{cases} \quad (24)$$

4) Selection

The next step is to select target vector or trial vector using the Equation (25) for next generation.

$$X_{i,j}^{(t+1)} = \begin{cases} U_{i,j}^{(t)} & \text{if } f(U_{i,j}^{(t)}) \leq f(X_{i,j}^{(t)}) \\ X_{i,j}^{(t)} & \text{else} \end{cases} \quad (25)$$

where f (.) - Fitness function

If the trial vector yields an equal or lower value of fitness function, it replaces the corresponding target vector in next generation; otherwise the target vector is retained in the population. Hence, the population gets either better or remains the same in fitness status, but never deteriorates. Stop the process and print the best individual if the stopping criterion is satisfied, else go back to mutation.

V. RESULTS AND DISCUSSION

A. Tools and Test systems

Programming codes for DE was developed using MATLAB 7.10.0 and SCOPF was solved with modified version of Matlab power simulation package MATPOWER 4.0b4 [19]. DE algorithms has been tested on IEEE 6 bus test system .The initial parameter values adopted for PSO and DE algorithms are presented in TABLE I. Simulations are performed in a computer with Intel i3 processor 2.66GHz and 4GB RAM.

TABLE I. INITIAL PARAMETER VALUES OF DE

Parameters	Values
Population Size	20
Number of iterations	200
Number of variables	2
Scaling Factor	0.8
Crossover Ratio	0.8
Convergence criteria	10^{-6}

B. IEEE 6 bus test system

IEEE 6 bus system has 6 buses, 11 transmission lines, 3 generators and 3.The data for the system are on 100 MVA base. The real and reactive power demand for base case is 210 MW, 210 MVAR respectively.

- Results for bilateral model

The proposed bilateral transaction matrix is given in TABLE II and the secured bilateral transaction matrix is determined and is given in TABLE III.

TABLE II. PROPOSED BILATERAL TRANSACTION MATRIX

Value of transaction between generator and load bus (p.u)		
T(1,4)=0.2	T(1,5)=0.4	T(2,4)=0.4
T(3,4)=0.1	T(3,5)=0.3	T(3,6)=0.7

TABLE III. SECURED BILATERAL TRANSACTION MATRIX

Value of transaction between generator and load bus (p.u)		
T(1,4)=0.1	T(1,5)=0.4	T(2,4)=0.1
T(3,4)=0.1	T(3,5)=0.3	T(3,6)=0.2

In order to verify the effects of optimal location of FACTS devices four cases were investigated.

Case 1: SCOPF without FACTS & without considering line limits
Case 2: SCOPF without FACTS considering line limits
Case 3: SCOPF with TCSC considering line limits
Case 4: SCOPF with SVC considering line limits.

TABLE IV. BIDDING COST OF IEEE 6 BUS SYSTEM

Generator Number	Bidding Cost
1	11 ($/Mwhr)
2	15 ($/Mwhr)
3	12 ($/Mwhr)

TABLE V. REAL POWER GENERATION PROFILE FOR IEEE 6 BUS SYSTEM

	Case 1	Case 2	Case 3	Case 4
P_{g1}	107.87 MW	60 MW	60 MW	60 MW
P_{g2}	50 MW	40.MW	40 MW	40 MW
P_{g3}	60MW	110MW	110 MW	40 MW

TABLE VI. REACTIVE POWER GENERATION PROFILE FOR IEEE 6 BUS SYSTEM

	Case 1	Case 2	Case 3	Case 4
Q_{g1}	55.79 MVAR	15.95 MVAR	55.37 MVAR	79.84 MVAR
Q_{g2}	46.21 MVAR	74.35 MVAR	43.71 MVAR	89.57 MVAR
Q_{g3}	77.22 MVAR	89.62 MVAR	79.26 MVAR	100 MVAR

In TABLE V, real power generation values of three generators are summarized. From this table it is clear that real power generation at all the three generators are within their limits. In TABLE VI, reactive power generation values are given. From the results it is understood that reactive power generation at all the generators are satisfying the limits. Real power values and reactive power values are plotted in Fig.4 and Fig.5

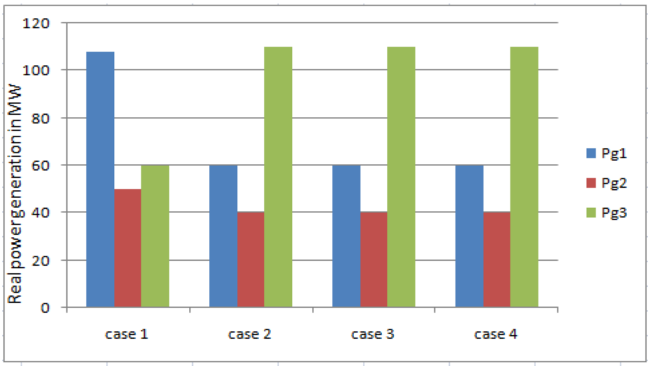

Fig.4. Real power generation profile

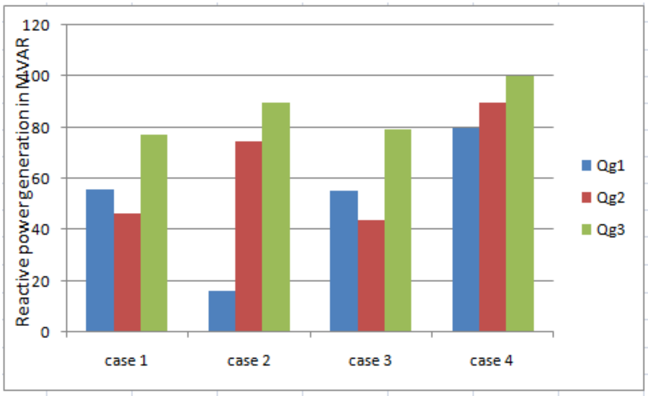

Fig.5.Reactive power generation profile

TABLE VII. OPTIMAL GENERATION PROFILE FOR IEEE 6 BUS SYSTEM

Cases of Analysis	Case1	Case2	Case3	Case4
Location of FACTS devices	-	-	Line 9 (3-6)	Bus 5
FACTS device settings	-	-	X_{TCSC}= -0.16 p.u.	Q_{SVC}= -73.96 MVAR
Total active power generation cost	2375.49 ($/hr)	2389.84 ($/hr)	**2372.56 ($/hr)**	**2370.25 ($/hr)**
Installation cost of FACTS devices	-	-	151.34 ($/hr)	129.78 ($/hr)
Total cost	2375.49 ($/hr)	2389.84 ($/hr)	**2523.9 ($/hr)**	**2500.03 ($/hr)**

In TABLE VII, location and parameter setting of TCSC and SVC, active power generation cost, installation cost of FACTS devices are given. Active power generation cost is calculated with the use of bidding cost which is given in TABLE IV. From TABLE VII it is understood that active power generation cost is 2372.56($/hr) while using DE algorithm, which gives the result as line 9(3-6) is the best location of placing TCSC.

In addition to that parameter setting of TCSC has found by DE algorithm and minimum cost of active power generation has obtained. It shows that effectiveness DE such as less computation time and minimum active power generating cost by the placement of TCSC at optimal location and its parameter setting.

Optimal location of SVC and Parameter setting of SVC has found by the proposed method. By placing SVC at optimal location (bus 5) the active power generating cost has further reduced from 2372.56($/hr) to 2370.25($/hr).Comparison between cost of active power generation, installation cost of FACTS devices, total cost are plotted in Fig.6.

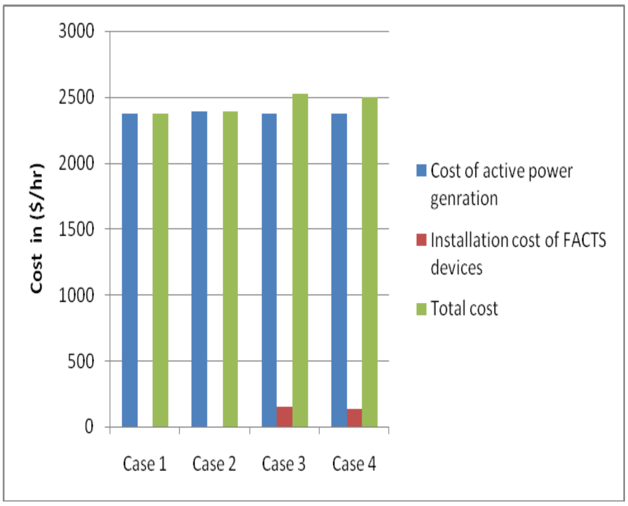

Fig.6. Comparison of total cost at all cases

Apparent power flow in IEEE 6 bus system with TCSC in line 3-6and SVC in bus 5 are summarized in TABLE VIII.

TABLE VIII. APPARENT POWER FLOW PROFILE (IN P.U.) FOR IEEE 6 BUS SYSTEM

Line i-j	MVA limit	Case 1	Case 2	Case 3	Case 4
1-2	0.4	0.0524	0.0632	0.0461	0.0418
1-4	0.6	0.3552	0.3991	0.5111	0.3271
1-5	0.4	0.2560	0.2816	0.2312	0.2255
2-3	0.4	0.1156	0.1057	0.0356	0.0404
2-4	**0.6**	**0.6427**	**0.6000**	**0.5894**	**0.5069**
2-5	0.3	0.2422	0.2314	0.2582	0.2027
2-6	0.9	0.2787	0.2764	0.3157	0.2816
3-5	0.7	0.3334	0.3120	0.2909	0.2406
3-6	0.8	0.7759	0.7536	0.6984	0.6405
4-5	0.2	0.0527	0.0519	0.6310	0.1379
5-6	0.4	0.0902	0.0770	0.0723	0.0731

From TABLE VIII it is understood that while placing TCSC at line 3-6 with the parameter setting obtained, the loading of the line 2-4 has now reduced to 98.23%, while placing SVC in bus 5 the loading of line 2-4 has further reduced to 84.48%.

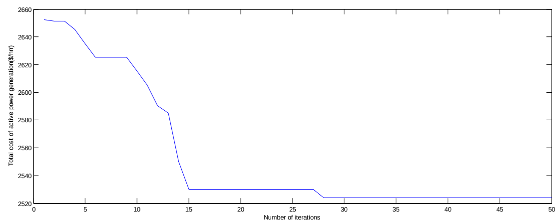

Fig.7 Convergence characteristics of DE algorithm with TCSC

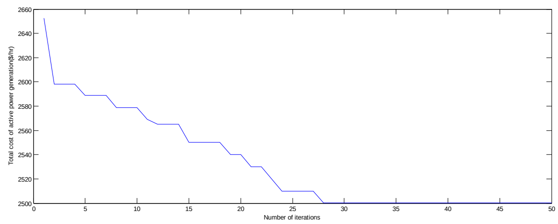

Fig.8 Convergence characteristics of DE algorithm with SVC

From Fig.7 and Fig.8, it is understood that in both the cases DE convergences faster with optimal value of objective function.

TABLE IX. STATISTICAL DETAILS OF DE ALGORITHM UNDER NORMAL OPERATING CONDITION

Compared item	With TCSC	With SVC
Fcost-Best ($/hr)	2523.9	2500.03
Fcost-Worst ($/hr)	2652.52	2598.05
Fcost-Average ($/hr)	2588.21	2549.04
Standard deviation	9.80359915E-12	4.617035E-12

Statistical details of DE algorithm for IEEE 6 bus system is shown in TABLE IX. From the standard deviation value given in TABLE IX it is clear that DE is more robust.

VI. CONCLUSION

In deregulated electricity market, because of environmental right-of-way and cost problems, various techniques are utilized to solve the problems of power transmission network without network expansion. Installation of TCSC and SVC devices in a power system improves the system security under normal and contingency operating conditions. The effectiveness of TCSC and SVC devices greatly depends on where the devices are located. In this work DE algorithm was used to obtain the optimal location of TCSC and SVC for SCOPF problem. Minimization of active power generation cost and installation cost of TCSC, SVC are considered as optimization criterion.

Simulations were performed on IEEE 6 bus test system. From the results it is understood that, DE is more effective, easy to use, robust algorithm having less computational time and faster convergence characteristics for optimal location FACTS devices in transmission system to SCOPF problem for Bilateral Model of deregulated electricity market.

Among the two FACTS devices used, SVC gives minimum cost of active power generation and minimum installation cost than TCSC. To conclude, for optimal location FACTS devices in transmission system to SCOPF problem for Bilateral Model of deregulated power system with FACTS devices using the computational intelligence algorithm, DE with SVC gives better performance.

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Biography

I.Catherine Divya is pursuing her postgraduate degree in Power Systems Engineering at Kamaraj College of Engineering & Technology, Virudhunagar, Anna University, Chennai, Tamil Nadu. She completed her undergraduate degree in Electrical & Electronics Engineering in the year 2012 at KLN College of Engineering, Anna University, Chennai, Tamil Nadu. Her main area of interest includes application of FACTS technology and computational intelligence techniques to solve power system problems.

S.Nagalakshmi has completed Ph.D. in the faculty of Electrical Engineering at Anna University, Chennai, Tamil Nadu. She completed her postgraduate degree in Power Systems Engineering in the year 2000 and undergraduate in Electrical & Electronics Engineering in the year 1999 at Madurai Kamaraj University, Tamil Nadu. She is working as Assistant Professor in the Department of Electrical & Electronics Engineering, Kamaraj College of Engineering &Technology, Virudhunagar, Tamil Nadu. Her main research area of interest includes power system restructuring,