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Optimal Number, Location And Sizing Of FACTS Devices For Optimal Power Flow Using Genetic Algorithm

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Abstract

This work applies genetic Algorithm to determine the optimal location, number, and sizing of Flexible AC Transmission Systems (FACTS) devices in power system to improve power system performance quality. The challenge in this study is considering a mixture of various objective functions, which are economic considerations as minimizing total generation cost and FACTS devices investment cost in addition to minimizing the system losses, holding voltage profile within acceptable limits, and considering minimization of reactive power flow on power system lines.

The optimization process is developed without missing MVA line flow limits cost and insuring that iteration counter increases towards its final value at convergence. A good simulation results can be obtained by minimizing all the objective functions and satisfying all the constraints. Shunt and series types of FACTS devices (SVC and TCSC) had been introduced. All objective functions have been solved and simulated by controlling the active power of the generators and reactive power of shunt and series compensator with respect to GA parameters. An IEEE30 bus system is used to demonstrate the effectiveness of the proposed fitness function based on (BGA) as an optimization tool and yields efficiency in improvement of power system performances. The results indicate that the proposed optimization using several methods like Weighted Sum method and Penalty Function method are available for finding the best solution. That approach with careful adjustment of the weight and penalty coefficients is a powerful optimization, may yield better solutions to a set of engineering problems than those obtained using a single objective function.

Keyword: Binary genetic Algorithm (BGA); optimal power flow (OPF); Flexible AC Transmission systems (FACTS).

1. Introduction

Due to the rapid extension in industries, power demand has increased substantially, while the expansion of generation and transmission has been limited. Some of the transmission lines and generators are working under overload conditions which effect on the overall power system stability. Flexible AC transmission lines (FACTs) has been applied successfully for solving the power systems stability problems, increase power transmissions, reactive power compensation, voltage stability enhancement, and power factor corrections [1-24]. So that the optimal location of FACTS devices, their optimal parameters, and their control systems are very important in order to evaluate the goal of their insertion in power systems. An appropriate models of (FACTS) shunt-series controllers for multi-objective optimization has been developed [25]. A multi-objective optimization approach is applied to determine the optimal location of FACTS shunt-series controllers. The optimal location and optimal parameters of the FACTS controllers have to be selected correctly to provide voltage stability and improve power system security [26]. The singular analyses of the power system Jacobian matrix are applied to identify the optimal location of shunt FACTS devices in large power systems. The Genetic algorithm (GA) has been applied for determining the location of FACTS controllers, their type and rated values [27]. Various FACTS controllers, Static Var controller (SVC), Thyristor Controlled Series Compensator (TCSC) and Unified power Flow Controller (UPFC) were considered. The used GA approach is an effective method for finding the optimal choice and location of FACTS controllers and also in minimizing the overall system cost. The Particle Swarm Optimization (PSO) technique has been applied to find optimal location of (FACTS) devices to achieve maximum system load-ability with minimum cost of installation of FACTS devices [28]. Different types of FACTS devices were considered which are, thyristor controlled series compensator (TCSC), static VAR compensator (SVC), and Unified power flow controller (UPFC). Transmission networks are operated near to their constraints under deregulated environment, so that installing FACTS devices can be useful in secure system operation. In order to maximize their investment surpluses, a new algorithm for optimal location of FACTS devices has been introduced [29]. The goal of such algorithm is to maximize the capacities in transmission network. A new method based on sensitivity analysis and extended equal area criterion (EEAC) is implemented for optimal location and capability of FACTS devices in a power system. The optimal location and capability of Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) in power systems is investigated. The power systems and transient stability improvement are the main goal [30]. The non-dominated sorting genetic algorithm (NSGA-II) with the feature of adaptive crowding distance has been proposed for solving multi-objective optimal power flow (MOOPF) problem. The technique is applied to determine the optimal location and capacity of FACTS devices in power system. Two types of FACTS devices (TCSC and SVC) were modeled and analyzed to enhance the steady state performance of power system [31]. The residue factor is implemented for determining the optimal location of FACTs devices to damp power systems oscillations [32]. The Sequential Quadratic Programming (SQP) approach has been used for determining the optimal location and optimal size of FACTs devices needed for power systems voltage stability enhancement. The second stage the Simulated Annealing (SA) based optimization method is used to find the optimal solution [33]. The sequence component has been applied for determining the optimal location and control of FACTs devices in unbalanced power systems. A Three-phase power flow modelization has been implemented [34]. A new multi-objective planning framework, namely non-dominated sorting improved harmony search (NSIHS), has been implemented to evaluate the impact of FACTS location for an improvement of voltage stability. This approach is based on the modify HS algorithm which has been extended to the multi-objective optimization problem by non-dominated sorting and ranking with crowding distance strategy[35].A Non-traditional optimization technique, modified particle swarm optimization (MPSO) is implemented to optimize the various process parameters involved of FACTS devices in a power system. The FACTs devices location, parameters, and their rated value were considered [36].

The Genetic Algorithms (GA) optimization technique has been applied to determine the optimal location of FACTS devices to improve voltage stability margin and minimize reactive power loss of the power systems. The location of FACTS devices, type, cost, and parameter values are optimized simultaneously [37]. A criticism of Evolutionary Algorithms might be the lack of efficient and robust generic methods to handle constraints [38]. The GA is a search process which can be applied to constrained problems; the constraints may be included into the fitness function as added penalty terms as in case of (MVA line flow limits and Convergence). Penalty terms are added to the fitness function. In this way the invalid solutions are considered as valid but they are penalized according to the degree of violation of the constraints. This method is probably the most commonly used method for handling problem constraints and is implemented in many variations [39-42] However, it imposes the problem of building a suitable penalty function for the specific problem, based on the violation of the problem's constraints, that will help the GA to avoid infeasible solutions and converge to a feasible (and hopefully the optimal) one.

The paper presents the application of (BGA) to seek the optimal location, number, and sizing of Flexible AC Transmission Systems (FACTS) devices in power system to improve power system performance. The challenge in this study is considering a mixture of various objective functions, which are economic considerations as minimizing total generation cost and FACTS devices investment cost in addition to minimizing the system losses, holding voltage profile within acceptable limits, and considering minimization of reactive power flow on power system lines.

2. Mathematical Model of FACTS Devices

TCSC is modelled simply to just modify the reactance of transmission line. *TCSC* acts as the capacitive or inductive compensator by modifying reactance of transmission line. This changes line flow due to change in series reactance illustrated in Fig. 1(a). In this paper TCSC is modelled by changing transmission line reactance as follows [43]:

$$X_{TL} = X_{TL} + r_{TCSC}\, X_{TL} \tag{1}$$

where X_{TL}= reactance of transmission line, r_{TCSC} =compensation factor of TCSC.
TCSC reactance is chosen between $-0.7X_{TL}$ to $0.2X_{TL}$. SVC at Fig. 1(b), can be used for both inductive and capacitive compensation, reactive power drawn by SVC, which is the same as the injected power to bus k, is written as [44]:

$$\Delta Q_k = Q_{svc} = -B_{SVC}\ V_k^2 \tag{2}$$

SVC chosen between -20 to 20 Mvar

3. Optimal Power Flow Formulation

The optimal power flow problem is to optimize the performance of a power system in terms of one or more objective functions while satisfying several equality and inequality constraints. Generally the problem can be formulated as a nonlinear and constrained optimization problem [42]:

$$\text{Minimize: } f(x,u) \tag{3}$$

$$\text{Subject to: } g(x,u) = 0\ ; \tag{4}$$

$$h(x,u) \le 0 \tag{5}$$

where *u*: Vector of system state variables ; *x*: Vector of problem control variable

f(x, u): Objective function to be minimized

g(x, u) : Equality constraints represents non-linear load flow equations.

h(x, u): Inequality constraints i.e. system functional operating constraints.

Some constraints include entire power flow equations, the optimal power flow Subject to:

Equivalent constraints:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{nb} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] = 0 \quad (7)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{nb} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} cos(\delta_i - \delta_j)] = 0 \quad (8)$$

Inequality constraints: Upper and lower limits on the active and reactive generations is given in Appendix A:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \qquad \forall\ i\ \varepsilon\ ng \quad (9)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \qquad \forall\ i\ \varepsilon\ ng \quad (10)$$

Where i=1,2…nb is the number of buses, P_G and Q_G are the generator real and reactive power respectively, V_G bus voltage, δ voltage angle of bus, P_D and Q_D are the real and reactive loads respectively, G_{ij} and B_{ij} are the transfer conductance and susceptance between bus i and bus j respectively.

4. Problem Formulation

Here, a problem with multi-objective functions is formulated to be minimize, total generation cost, FACTS devices investment cost, the system real power losses and the voltage deviation. To help the GA to avoid infeasible solutions and converge to a feasible, incorporating constraints into the fitness function of a GA by using penalty factors w_i. The presented technique gives the GA a significantly better chance of locating the global optimum. That was applied to reactive power flow on lines, line-flows deviation and insure iteration counter increases towards its final value at convergence. That result in a complicated search hyper-surface.

4.1 Fuel cost of generation units

The objective function considering minimization of generation cost as in [41, 45-46] can be represented as given in equation (4)

$$f_1 = w_1 \sum_{i=1}^{ng} a_i P_{Gi}^2 + b_i P_{Gi} + c_i \quad (\$/h) \quad (6)$$

Where ng is the number of generators, P_G is the active power outputs of the generators and a, b and c are the generating cost coefficients in ($ /hr) as given in Appendix A.

4.2 FACTS devices investment

Polynomial cost function of FACTS devices is presented in Siemens AG Database and used for FACTS allocation study as used in [47]. The cost function of TCSC is expressed as: $C_{TCSC} = 0.0015\ S^2 - 0.7130\ S + 153.75$ (12)

Where C_{TCSC}: cost of TCSC in $/KVar and S is the operating range of TCSC in MVAr.

SVC Cost Function: In $/KVar basis the cost function is expressed as [29]:

$$C_{SVC} = 0.0003\ S^2 - 0.3051\ S + 127.38 \quad (11)$$

where, S is the operating range of the SVC device in MVar.

The total FACTS devices cost is expressed as

$$f_2 = w_2(\sum C_{TCSC} + \sum C_{SVC}) \quad (12)$$

The cost of FACTS installation$= S f_2 \frac{1000}{w_2 \times 8760 \times life\ time}\ (\$/h)$ (13)

Inequality constraints. Upper and lower bounds in the FACTS parameters (Table. 2):

$$X^{min} \leq X_{FACTS} \leq X^{max} \quad (14)$$

4.3 Transmission lines loss

Considering minimization of real power loss as in [45,48-49] can be represented as:

$$f_3 = P_{Loss} = \sum_{i=1}^{nl} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)) \quad (15)$$

Where nl is the total number of transmission lines.

4.4 Reactive power flow

The objective function considering minimization of reactive power flow on power system lines. This objective reduces the FACTS size and numbers, represented as:

$$f_4 = w_4\left(-V_j^2(B_{ij} + B_{sh}) + V_iV_j\left(G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)\right)\right) \quad (16)$$

4.5 Voltage Level (VL)

Inequality constraints of the system voltage

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (17)$$

Where $V_i^{min} = 0.95$ and $V_i^{max} = 1.1$

For voltage levels between 0.95 to 1.1 p.u, the value of objective function is equal to 0. And take penalty outside this range, so the value increase to w_5 [40].

$$f_5 = \begin{cases} 0 & if\quad 0.95 < V_i < 1.1 \\ w_5 & otherwise \end{cases} \quad (18)$$

4.6 Line-flow deviation

Considering minimization of apparent power flow on power system lines to insure not exceeding the limit of MVA of lines. This can be represented as:

$$f_6 = w_6 \left(V_i (V_i - V_j)^* Y^*_{bus\ ij} - \frac{LF}{baseMVA} \right) \quad (19)$$

Where LF is the limit lines MVA as given in Appendix B.

4.7 Optimal power flow convergence

Solving the power flow problem by iterative step to insure iteration counter increases towards its final value at convergence by penalty function method.

$$f_7 = w_7 \left(\sum_{i=1}^{ng} P_{Gi} - \sum_{j=1}^{nb} P_{Dj} - \sum_{k=1}^{nl} P_{Loss(k)} \right) \quad (20)$$

To obtain the total fitness function, the weighted sum method of all components of cost function are linearly evaluated

$$\text{Total fitness function} = \sum_{i=1}^{7} w_i \times f_i \quad (21)$$

Where the weighting factors w_i, inserted in the each cost term.

5. Proposed Method

The Genetic Algorithm (GA) was developed by the evolutionary theory of Darwin. A series of initial solutions that meet all conditions are created randomly and then the control parameters are encoded to solve the seven OPF problems. Fitness function is developed to generate more resistant generations using operators of crossovers and mutations in each iteration step as shown in Fig.2.

The proposed method aims to give optimal number, location and values of both shunt and series type of FACTS and also gives optimal values of six-generator power. The method used digital GA (Table 1) with 5 strings and 34 variables to achieve the total cost function. The used chromosome structure has the first string with 6 parameters which is used to set power for the five generators units, within operation constrain limits and limiting the slack bus power. The next four strings dealing with FACTS locations and values (Table.2). Parameters of the GA at strings 2-4 take place to obtain the location of FACTS devices. Seven is the maximum number of SVC and TCSC devices. Ranking the chromosomes according to the total fitness function. Due to the influences of the costs of minimizing the reactive power flow on lines and FACTS devices investment. The chromosome with small numbers of FACTS devices will have a high rank. That will successfully limit the total number of FACTS devices inserted in the system.

6. Simulation Results

The load flow is performed for the given IEEE 6-M/30-bus system. The bus data and line data are taken from [50]. The studies system schematic diagram is as shown in Fig. 3. The choice of appropriate penalty terms for each terms of the fitness from f_1 to f_7 are taken as 1, 0.1, 1, 10, 100, 100, 1000 respectively. The chromosome with lowest cost (best solution) avoid all penalties and a sufficient minimum cost for all terms of the total cost that clearer in Table 3, incorporated into the power system, carrying out OPF process to give the best total cost 862.6492. The base case given by American Electric Power does not contain any compensators. The enhancement in the total performances of the power system as illustrated in table 4. Convergence curve of the total minimum cost function shown in fig.4. The reduction in the number of FACTS units over GA generation are illustrated in Fig.5. Comparative results at base case and after optimization for: system powers, active (P) and reactive (Q) flow on lines are shown in Fig.6. Comparative results at base case and after optimization for active power loss and lines flow in MVA are shown in Table 5. Enhancement in generators reactive power(Q) and power factor (P.F.) in Fig.7. In addition, the improvement in the power system buses voltage profile performance is clarified in Fig.8.

7. Conclusion

The choice of appropriate penalty terms for constrained optimization is a serious problem. Some constrains of power system as reactive power flow on lines, line-flows deviation and OPF convergence are incorporating into fitness function using penalized degree of violation. This proposed technique is success to guide the search towards the optimum and enhancement of many performances of power system. Result in a smoother hyper-surface. Ranking method successfully reduced the suggested FACTS numbers. Also using a large number of GA variables helped in a good system quality. Brief comparatively study results on standard test system confirmed the effect of optimized FACTS device to improve power system performances on lines and buses, in addition to reduce the annual monetary operating cost. Studied system overall objective functions, have been considered in the study to indicate the powerful of the proposed approach. The proposed BGA optimization technique have been evaluated through the IEEE 30-bus power system.

APPENDIX

A. Generating limits and cost coefficients for IEEE-30-bus system [41,50-52]

bus No.	V_G^o	P_{Gi}^{max}	P_{Gi}^{min}	Q_{Gi}^{max}	Q_{Gi}^{min}	a($/MW^2)	b($/MW)	c ($)
1	1.06	200	50	-	-	0.00375	2	0

2	1.043	80	20	100	-20	0.0175	1.75	0
5	1.01	50	15	80	-15	0.0625	1	0
8	1.01	35	10	60	-15	0.00834	3.25	0
11	1.082	30	10	50	-10	0.025	3	0
13	1.071	40	12	60	-15	0.025	3	0

B. MVA-Limits for 41 line of IEEE-30 bus system [50,52]

Line No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MVA limit	130	130	65	130	130	65	90	70	130	32	65	32	65	65
Line No.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
MVA limit	65	65	32	32	32	16	16	16	16	32	32	32	32	32
Line No.	29	30	31	32	33	34	35	36	37	38	39	40	41	
MVA limit	32	16	16	16	16	16	16	65	16	16	16	32	32	

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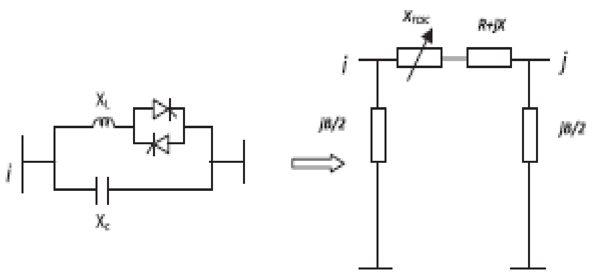

Fig 1.(a) TCSC: basic structure and model

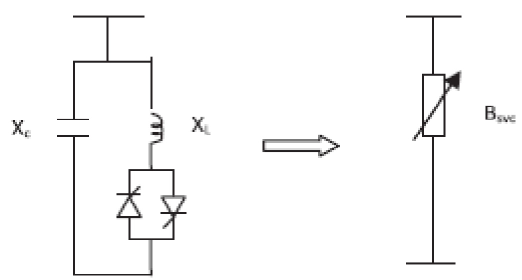
Fig 1.(b) SVC: basic structure and model

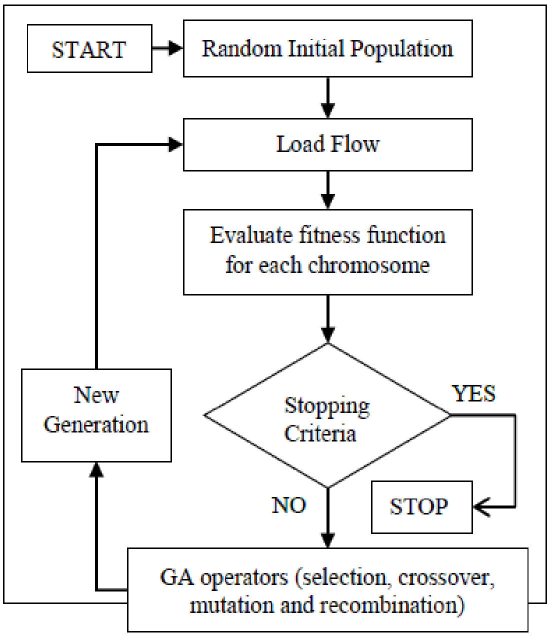

Fig.2 Application of GA to OPF Problem

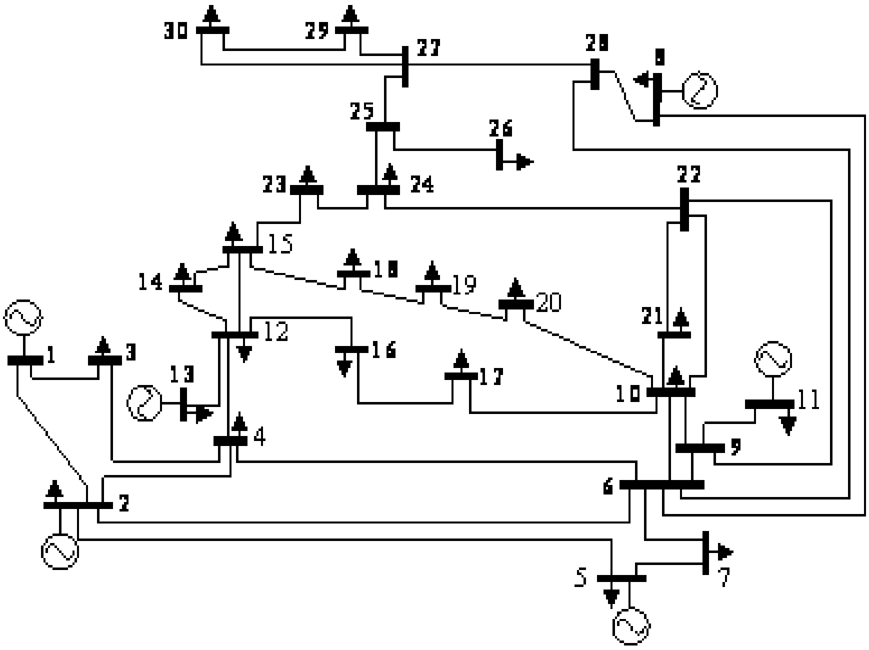

Fig.3. IEEE30 Test System

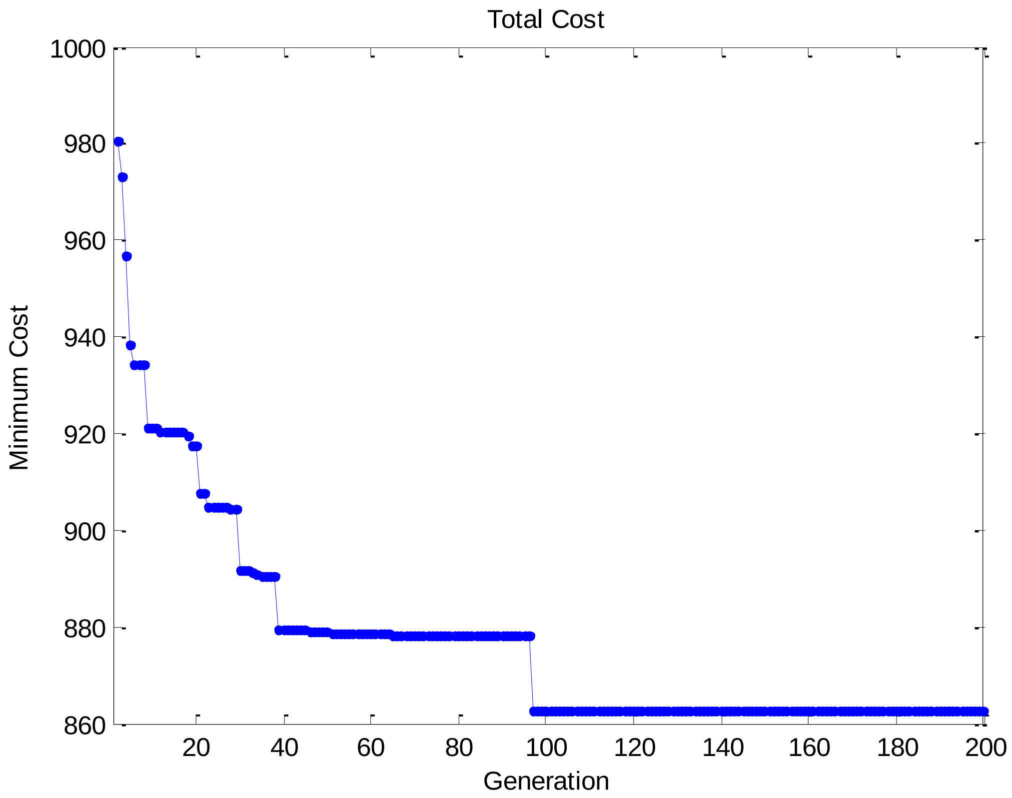

Fig.4 convergence curve of the total fitness function

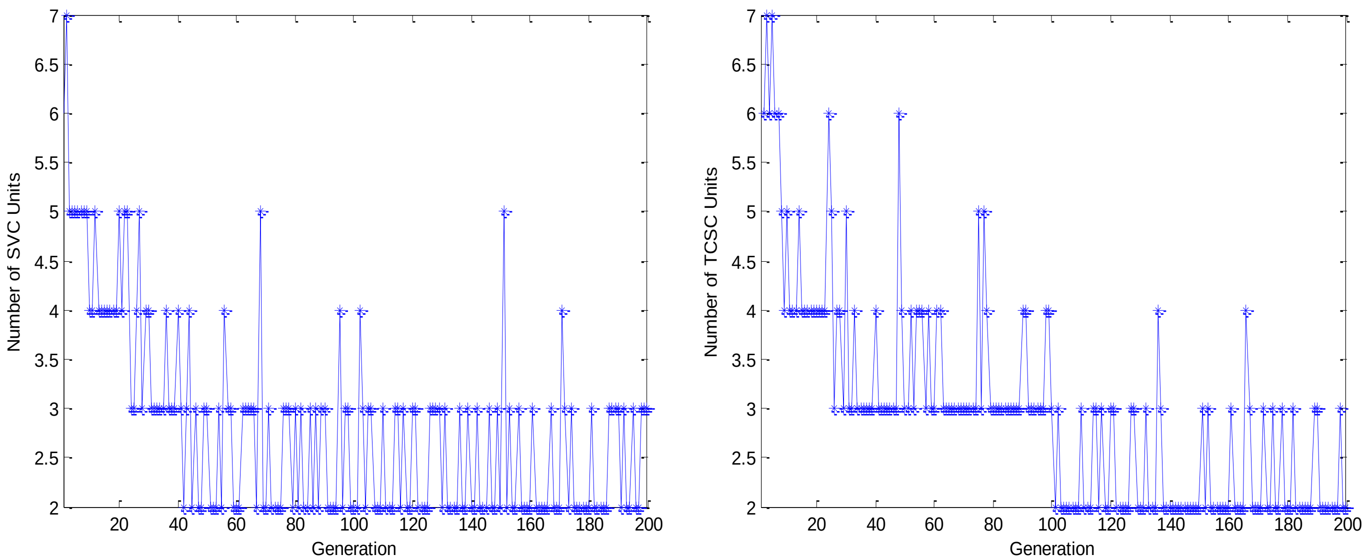

Fig.5 Optimized Number of (SVC and TCSC) units during GA generation.

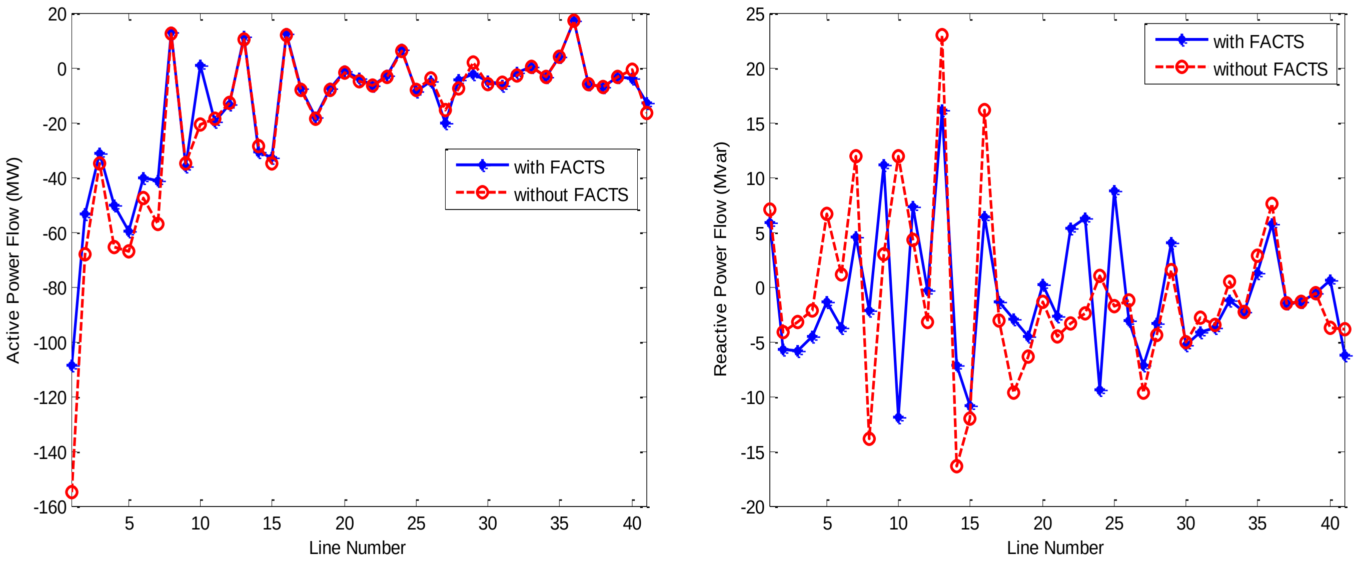

Fig.6 Optimal powers (P and Q) flow on lines with and without FACTS devices

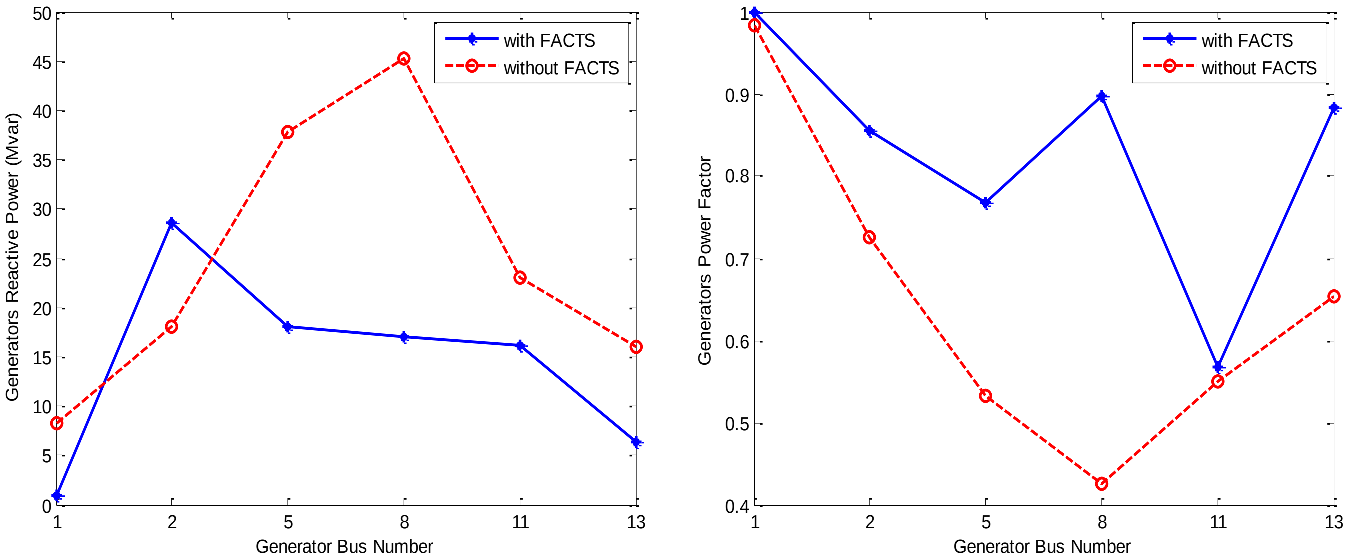

Fig.7 Generators buses (Q and P.F.) after and before using optimized FACTS

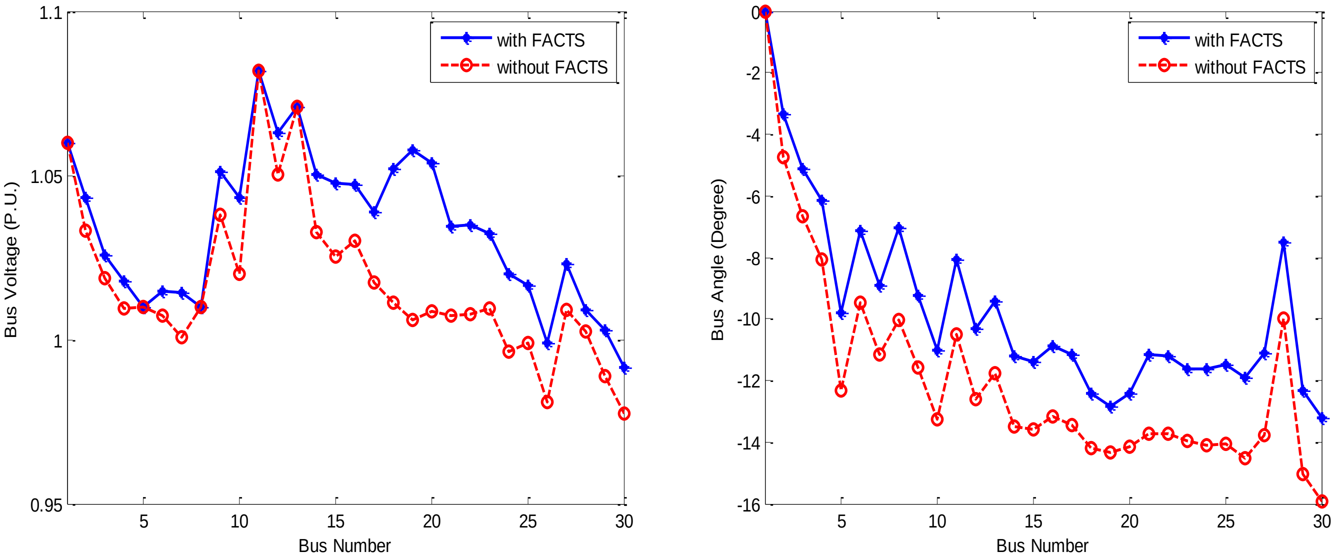

Fig.8 Voltage and Angles of the buses after and before using optimized FACTS

Table.1 GA parameters setting

Population size	80 chromosome
No. of GA parameters	34 variable
Parameter size	16 bits
Mutation rate	0.01
Selection	0.5
Max. GA generations	200 iterations
fitness limit	Zero

Table 2. Chromosome structure

String number	Gene Number	Function	GA parameters constrains	
			Minimum	Maximum
1	1 – 6	Generators-power	P_{Gi}^{min}	P_{Gi}^{max}
2	7 – 13	SVC-bus location	1	30
3	14 – 20	SVC-Values	-20(Mvar)	20(Mvar)
4	21 – 27	TCSC-line location	1	41
5	28 – 34	TCSC-Values	$-0.7X_{TL}$	$0.2X_{TL}$

Table 3. Chromosome structure for best solution

Generators (MW)	165.4	47.138	21.527	34.857	11.15	12.13
SVC-bus location	19th	7th	22th			
SVC Value (Mvar)	19.158	19.837	4.9339			
TCSC-line location	25th	27th				
TCSC Value (P.U)	0.069192	-0.63664				

Table 4. Comparative analysis

	IEEE30 (base-case)	Optimized IEEE30
Total Generators power (MW)	296.759	292.16
Total Generators Reactive power (Mvar)	148.306	87.14
Total Power Loss (MW)	13.359	8.7576
Total Reactive Power Loss (MW)	22.106	4.8689
Fuel Cost ($/h)	833.35	797.55
FACTS cost ($/h) : project life time 5 years	-	15.45
Converge (Iterations)	7	5

Table 5. power loss and lines MVA comparative anlysis

Line	*Power-Loss*		*Flow in MVA*		*Line*	*Power-Loss*		*Flow in MVA*	
	Base	OPF	Base	OPF		Base	OPF	Base	OPF
1-2	4.340	2.102	159.35	111.02	16-17	0.035	0.019	6.70	4.98
1-3	2.038	1.223	70.87	54.83	15-18	0.059	0.066	7.60	8.22
2-4	4.341	0.545	35.36	31.96	18-19	0.011	0.028	4.26	6.95
3-4	0.555	0.327	66.04	51.04	19-20	0.012	0.04	6.07	11.45
2-5	2.112	1.650	69.13	61.49	10-20	0.065	0.127	8.48	12.15
2-6	1.291	0.913	48.69	41.18	10-17	0.006	0.01	4.38	5.79
4-6	0.400	0.198	58.60	41.55	10-21	0.115	0.147	18.55	21.47
5-7	0.146	0.077	17.22	12.96	10-22	0.054	0.021	8.80	5.57
6-7	0.333	0.371	35.68	38.07	21-22	0.001	0.002	2.470	4.79
6-8	0.069	0.015	24.34	11.04	15-23	0.060	0.050	7.94	7.39
6-9	0.000	0.000	19.16	20.55	22-24	0.044	0.071	6.27	8.13
6-10	0.000	0.000	13.33	13.39	23-24	0.025	0.021	4.43	4.15
9-11	0.000	0.000	24.05	19.07	24-25	0.001	0.003	0.65	١,٢١
9-10	0.000	0.000	33.74	31.73	25-26	0.046	0.045	4.27	4.26
4-12	0.000	0.000	37.23	35.56	25-27	0.026	0.016	4.910	3.88
12-13	0.000	0.000	19.65	13.62	28-27	0.000	0.000	18.91	17.94
12-14	0.090	0.069	8.960	7.940	27-29	0.089	0.086	6.42	6.41
12-15	0.285	0.202	21.78	18.56	27-30	0.170	0.162	7.29	7.29
12-16	0.099	0.068	10.75	9.030	29-30	0.035	0.034	3.75	3.75
14-15	0.013	0.005	2.520	1.530	8-28	0.008	0.010	3.36	4.13
					6-28	0.048	0.033	16.86	14.0