Electrical Power and Energy Systems 78 (2016) 470–479

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Loadability enhancement with FACTS devices using gravitational search algorithm

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ARTICLE INFO

Article history:
Received 2 September 2015
Received in revised form 15 November 2015
Accepted 26 November 2015
Available online 23 December 2015

Keywords:
FACTS devices
Active power loss
Operating cost
Loadability
Gravitational search algorithm

ABSTRACT

In the present work, GSA (gravitational search algorithm) based optimization algorithm is applied for the optimal allocation of FACTS devices in transmission system. IEEE 30 & IEEE 57 test bus systems are taken as standards. Both active and reactive loading of the power system is considered and the effect of FACTS devices on the power transfer capacity of the individual generator is investigated. The proposed approach of planning of reactive power sources with the FACTS devices is compared with other globally accepted techniques like GA (Genetic Algorithm), Differential Evolution (DE), and PSO (Particle Swarm Optimization). From the results obtained, it is observed that incorporating FACTS devices, loadability of the power system increases considerably and each generator present in the system is being able to dispatch significant amount of active power under different increasing loading conditions where the steam flow rate is maintained corresponding to the base active loading condition. The active power loss & operating cost also reduces by significant margin with FACTS devices at each loading condition and GSA based planning approach of reactive power sources with FACTS devices found to be the best among all the methods discussed in terms of reducing active power loss and total operating cost of the system under all active and reactive loading situations.

Introduction

In power system, engineers and researchers are in process to reduce reactive power and transmission loss to boost system efficiency. Reactive power has a deep effect on the security of power networks as it influence voltages throughout the entire network. To increase the amount of active power that can be transferred across a congested transmission network, reactive power flows must be minimized. Likewise, increase in reactive power generation of a particular generator has impact on it's active power generation capacity. In addition, reactive power is essential (i) for the flow of active power through the transmission and distribution system and (ii) to maintain the voltage to deliver active power through transmission lines. Flexible AC Transmission System (FACTS) devices can be effective for static as well as for dynamic state of voltage control in power transmission and distribution. It's principal function is to inject reactive power into the system which helps to support the system voltage profile. FACTS devices regulate desired power flow in a power network provide the best voltage profile in the system as well as to minimise the system transmission loss.

The elementary idea of FACTS devices was first came into existence in 1988 [1]. Lagrangian decomposition approach is applied in [2] for active power congestion management. Optimal placement of capacitor in a radial distribution system is presented in [3]. An elaborative discussion for the optimum placement of series capacitor and phase shifter is presented in [4]. Sensitivity analysis and linear programming technique is presented for the optimal location and size of Static Var Compensator (SVC) in a connected power system in [5]. In [6], Authors have used TCSC device based on the use of LMP (Locational Marginal Pricing) difference and congestion rent. Real power performance index is used in [7], as an indicator for the determination of location of Thyristor Controlled Series Capacitor (TCSC) positions in a connected power network. In [8], solution of transmission system congestion management problem is addressed by the authors using TCSC where the system loadability is increased keeping in view of the voltage stability of the system. Optimal placement of TCSC for increasing loadability and minimizing transmission loss by Genetic Algorithm (GA) is presented in [9]. Use of static phase shifters and series power flow controller (SPFC) and Unified Power Flow Controller (UPFC) to increase power transfer capacity in transmission lines is described in [10]. Solution technique for the power flow problem with TCSC

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http://dx.doi.org/10.1016/j.ijepes.2015.11.114

and UPFC devices is presented in [11]. Enhancement of available transfer capacity with UPFC devices is described in [12]. Power flow control approach in consideration with available transfer capacity using static synchronous series compensator (SSSC), UPFC and STATCOM devices is discussed in [13]. Authors have used STATCOM, SSSC and UPFC devices in [14] for congestion management considering voltage stability as loadability limit. Authors have proposed a technique in [15], for the optimal coordination of SVC, TCSC and thyristor controlled phase angle regulator (TCPAR) on the basis of demand responses in the restructured power market. Optimal reactive power dispatch along with switchable TCSC and SVC devices is presented in [16]. Improvement in power flow control with TCSC, SVC and UPFC devices is presented in [17]. This paper shows how the system loadability improves with simultaneous use of multi type FACTS devices. An hybrid Genetic Algorithmic approach with TCSC and thyristor controlled phase shifter (TCPS) devices for optimal power flow is described in [18]. The placement of TCSC, TCPST, TCVAR and SVC devices in a power system using GA is discussed in [19]. Utility of different types of UPFC, TCSC, PCPST and SVC devices in deregulated electricity market is explained in [20]. In [21], congested areas of an interconnected power networks are determined and then TCSC's and SVC are allocated using GA based optimization technique to solve transmission congestion. In [22], authors have developed a model to solve congestion management problem by proper placement of unified power flow controller's (UPFC) in suitable locations of the power system. PSO based solution methodology is applied in determining proper size of UPFC to reduce the generation cost as well as congestion cost in a restructured power market in [23]. In order to minimize active power loss, improvement of voltage profile and enhancement of voltage stability, GSA is proposed in [24]. In [25], simulation results indicate that GSA can provide effective and robust high-quality solution for the OPF problem. Applicability of different computational algorithms for load ability enhancement with TCSC, SVC, TCPST devices is presented in [26]. In [27], authors have proposed the application of FACTS devices in a deregulated environment for the solution of combined active and reactive congestion management. In [28], authors suggested model of three FACTS devices i.e. SVC, TCSC and TCPAR and unified into new FDLF (n-FDLF) program. By using above said program, a model of the Hellenic power system is developed.

In the present work, authors have implemented GSA based optimization algorithm for the optimal planning of FACTS devices for the minimization of active power loss and operating cost of the system under different loading conditions. Moreover, ability of each generators to transfer active power in under different loading conditions are investigated where the steam input to each generators are kept corresponding to the base demand.

Modeling of facts devices

For an interconnected congested power network FACTS devices can be modeled as power injection model. The injection model describes the FACTS as a device that injects a certain amount of real and reactive power to a node. Both TCSC and SVC devices control the power flow and voltages by adjusting the reactance of the system. There are two possible characteristic for TCSCs; capacitive and inductive, to increase or decrease the transmission line reactance. These devices can cause increase in the transmission power capacity of lines, static voltage security margin enhancement, voltage profile improvement, and decrease in active power loss. SVCs have also capacitive and inductive characteristics and are predominantly utilized to improve and amend voltage in static and dynamic conditions, reduce reactive power loss, and enhances static voltage security margin. The injection power model and variable susceptance model shown in Figs. 1–3.

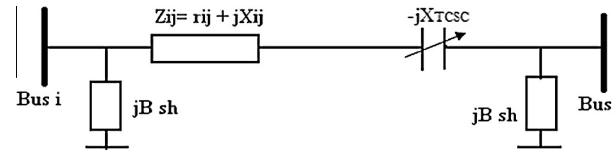

Fig. 1. TCSC model.

Cost function and problem formulation

The objective of the proposed work is to minimize the transmission loss of the system using FACTS devices under different loading conditions. Increase in transmission loss as well as problem of voltage stability is the main concern with the increased load. So, when the system loading is increased gradually, it requires reactive power support to maintain voltage stability. Hence the main aim of the present work is to reduce the real power loss which is expressed by Eq. (1) and to minimize voltage deviation at weak buses under different loading conditions.

$$P_L = \sum_{\substack{x=1 \\ k=(i,j)}}^{n} g_x(v_i^2 + v_j^2 - 2v_i v_j Cos\,\theta_{ij}) \tag{1}$$

where g_x is the conductance of line x, v_i, v_j are the voltages of ith and jth node respectively, and $\theta_{i,j}$ is the phase angle difference between ith and jth node.

Hence the objective of the present work is transmission loss minimization problem subject to the satisfaction of equality and inequality constraints. Cost functions for TCSC's and SVC's are given below:

TCSC:

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \text{ (US \$/kVar)} \tag{2}$$

SVC:

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38 \text{ (US \$/kVar)} \tag{3}$$

Here, S is the operating value of the FACTS devices. Energy cost is taken as 0.06$/kW h and cost functions are obtained from [20].

The main objective is to find the optimal location of FACTS devices along with network constraints so as to minimize the total operational cost and relieve transmission congestion at different loading conditions. Installation costs of various FACTS devices

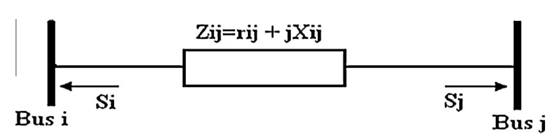

Fig. 2. TCSC injection model.

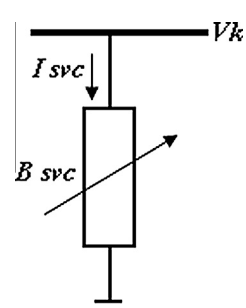

Fig. 3. Variable susceptance model of SVC.

and the cost of system operation, namely, energy loss cost are combined to form the objective function to be minimized. Without FACTS devices, transmission loss can also be minimized by optimization of reactive power, which is possible by controlling reactive generations of the generator's, controlling transformer tap settings, and by the addition of shunt capacitors at weak buses. As Var generations of the generators and controlling transformer tap settings within their defined limits do not contribute any cost to the operating cost of the system, here in the proposed approach setting of transformer tap positions and reactive generations of generators are included as controlling parameters along with the FACTS devices.

The objective function is combinatorial. It consists of two parts; first is the cost due to the energy loss and second is the cost due to investment of FACTS devices. So the optimization of the objective function requires not only minimization of cost of energy loss which is related with the minimization of transmission loss by FACTS devices but also a optimization problem of investment cost of FACTS devices.

The optimal allocation of FACTS devices can be formulated as:

$$C_{TOTAL} = C_1(E) + C_2(F) \tag{4}$$

where $C_1(E)$ is the cost due to energy loss and $C_2(F)$ is the total investment cost of the FACTS devices.

Objective function is minimized considering following active and reactive power balances and voltage magnitude constraints.

$$P_{ni}^{\min} \leqslant P_{ni} \leqslant P_{ni}^{\max} \tag{5}$$

$$Q_{ni}^{\min} \leqslant Q_{ni} \leqslant Q_{ni}^{\max} \tag{6}$$

$$V_{i}^{\min} \leqslant V_{i} \leqslant V_{i}^{\max} \tag{7}$$

Superscripts min, max are the minimum and maximum limits of the variables.

Then, the power flow equations between the nodes i–j after incorporating FACTS devices would appear as

<u>TCSC</u>:

$$P_{Gi} - P_{Di} + P_i \sum_{j=1}^{N-1} V_i V_j (G_{ij} \cos\theta_{ij} + Bij \sin\theta_{ij}) = 0 \tag{8}$$

$$Q_{Gi} - Q_{Di} + Q_{i(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \tag{9}$$

$$P_{Gi} - P_{Di} + P_i - \sum_{j=1}^{N-1} V_j V_j (G_{jj} \cos\theta_{jj} + B_{jj} \sin\theta_{jj}) = 0 \tag{10}$$

$$Q_{Gj} - Q_{Dj} + Q_{j(inj)} - \sum_{j=1}^{N-1} V_j V_j (G_{jj} \sin\theta_{jj} - B_{jj} \cos\theta_{jj}) = 0 \tag{11}$$

<u>SVC</u>:

$$Q_{Gi} - Q_{Di} + Q_{iL(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \tag{12}$$

where P_{Gi} and Q_{Gi} are the active and reactive generation and P_{Di} and Q_{Di} are the active and reactive demand at the ith node. G & B are the component of bus admittance matrix.

P_i and $Q_{i(inj)}$ are the real and reactive power flow change takes place at the nodes due to TCSC connected to a particular line between the nodes i and j. $Q_{iL(inj)}$ is the reactive power injection due to SVC. These changes in the power flow equations are taken into consideration by appropriately modifying the admittance bus matrix for execution of load flow in evaluating the objective function for each individual population of generation of Gravitational Search and other evolutionary algorithms as DE, GA and PSO.

TCSC	SVC	Transformer tap setting	Reactive Generation of Generators
4 nos.	4 nos.	4 nos.	5 nos.

Fig. 4. String variables for IEEE-30 bus system.

TCSC	SVC	Transformer tap setting	Reactive Generation of Generators
4 nos.	3 nos.	17 nos.	6 nos.

Fig. 5. String variables for IEEE-57 bus system.

The objective function is calculated for all the individual of the new generation and the procedure is repeated till the final goal is reached. It is to be mentioned that the modified power flow equations represented by Eqs. (8)-(12) are also to be incorporated in the load flow program in evaluating objective function. The number of each variables belonging to a particular type of parameter are shown in Fig. 4 and 5 for both IEEE-30 and IEEE-57 bus systems respectively.

Gravitational search algorithm

Gravitational search algorithm is a metaheuristic optimization technique based on Newton's law of gravity and motion. This algorithm was first developed by Rashedi et al. [23] in 2009. The working of this algorithm is greatly influenced by the motion and the mass of agents. Each agent experiences gravitational force of attraction with other agents present in the search space. Fitness of agents in the search space is characterized by their masses. Hence, GSA can be considered as collection of different masses. Heavier mass has bigger attraction force and attract other masses with a force proportional to the product of their masses and inversely proportional to the distance (not the square of distance) between masses.

The position of a mass corresponds to a solution in the search space. In due course of time all the masses or the agents will be attracted by the heaviest mass and the heaviest mass will represent the optimum solution in the search space.Initially, N number of agent are created and their positions are defined by

$$X_i = [x_i^1 \cdots x_i^n] \tag{13}$$

For i = 1, 2, ..., n. Force of attraction between an active gravitational mass and a passive gravitational mass at any specific time t is given by

$$F_{ij}(t) = G(t) \times \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + \in} [X_j(t) - X_i(t)] \tag{14}$$

where M_{pi} is the passive gravitational mass and which is ith agent and M_{aj} is the active gravitational mass which is the jth agent. R_{ij} is the Euclidian distance between the ith and jth mass. $\in$ is a small constant. The passive gravitational mass is attracted towards active gravitational mass.

Total force on ith agent is given by

$$F_i(t) = \sum_{i=1, j\neq 1} (rand) * F_{ij}(t) \tag{15}$$

where $rand$ is a random number in the interval [0, 1].

The acceleration of the ith agent at time t is given by

Table 1
Locations of different FACTS devices in the transmission network in IEEE-30 bus system.

TCSC in lines	SVC in buses
25, 41, 28, 5	21, 7, 17, 15

Table 2
Locations of different FACTS devices in the transmission network in IEEE-57 bus system.

TCSC in lines	SVC in buses
37, 13, 61, 57	49, 25, 38

$$\alpha_i(t) = \frac{F_i(t)}{M_i(t)} \tag{16}$$

Gravitational constant $G(t)$, at time t is computed as follows:

$$G(t) = G_0 \exp\left(-\alpha \frac{t}{T}\right) \tag{17}$$

where G_0 is the initial value of the Gravitational constant, chosen randomly, α is a constant, t is the current generation and T is the total number of generations.

The velocity and the position of the ith agent are updated by the following equation:

$$V_i(t+1) = rand_i \times V_i(t) + \alpha_i(t) \tag{18}$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{19}$$

Mass of each agent is determined by it's fitness. The masses of agents are updated by the following equation.

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{n} m_{ij}(t)} \tag{20}$$

where $m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)}$

In the present problem reactive power sources along with the amount of FACTS devices are represented by a string and each string is nothing but the solution agent in the search space. Each agent will have mass according to their fitness values evaluated from the objective function.

Table 3
Comparative study of total reactive power flow in line with GA, DE, PSO and GSA in IEEE-30 bus system.

Loading (%)	$\sum_l^{nl} Q_L$ Without FACTS	$\sum_l^{nl} Q_L$ With FACTS using GA	$\sum_l^{nl} Q_L$ With FACTS using DE	$\sum_l^{nl} Q_L$ With FACTS using PSO	$\sum_l^{nl} Q_L$ With FACTS using GSA
100	−0.2994	−0.4197	−3.5822	−0.3614	−0.6104
110	−0.0185	−0.4842	−1.1510	−1.1864	−0.2222
120	0.2862	−1.3166	−2.5170	−1.8457	−2.1400

Table 4
Operating cost and active power loss analysis without and with FACTS devices in IEEE-30 bus system.

Loading Pd and Qd (%)	Active power loss without FACTS devices in (pu)	Operating cost due to energy loss in ($) (A)	Active power loss with loss with FACTS devices in (pu)	Evolutionary methods with FACTS devices	Operating cost in ($) (B)	Cost of FACTS devices in ($)	Net saving (*A*–*B*)
100	0.0711	3,737,016	0.0406	GA	2.1786×10^6	44,664	1,558,416
			0.0406	DE	2.1770×10^6	43,064	1,560,016
			0.0445	PSO	2.4052×10^6	66,280	1,331,816
			0.0390	GSA	2.1481×10^6	98,260	1,588,916
110	0.0974	5,120,900	0.0585	GA	3.1222×10^6	47,440	1,998,700
			0.0584	DE	3.1222×10^6	52,700	1,998,900
			0.0639	PSO	3.4361×10^6	77,516	1,684,800
			0.0581	GSA	3.1224×10^6	68,700	1,998,500
120	0.1294	6,800,100	0.0839	GA	4.4915×10^6	81,716	2,308,600
			0.0839	DE	4.4915×10^6	81,716	2,308,600
			0.0891	PSO	4.7774×10^6	94,304	2,022,700
			0.0824	GSA	4.4230×10^6	92,056	2,377,100

Table 5
Operating cost and active power loss analysis without and with FACTS devices in IEEE-57 bus system.

Loading Pd and Qd (%)	Active power loss without FACTS devices in (pu)	Operating cost due to energy loss in ($) (A)	Active power loss with loss with FACTS devices in (pu)	Evolutionary methods with FACTS devices	Operating cost in ($) (B)	Cost of FACTS devices in ($)	Net saving (*A*–*B*)
100	0.2799	14,712,000	0.2165	GA	1.1440×10^7	60,760	3,272,000
			0.2168	DE	1.1465×10^7	69,992	3,247,000
			0.2276	PSO	1.2059×10^7	96,344	2,653,000
			0.2145	GSA	1.1429×10^7	154,880	3,283,000
110	0.4168	21,907,000	0.2997	GA	1.5840×10^7	87,768	6,067,000
			0.2997	DE	1.5846×10^7	93,768	6,061,000
			0.3155	PSO	1.6674×10^7	91,320	5,233,000
			0.2989	GSA	1.5830×10^7	119,816	6,077,000
120	0.6091	32,015,000	0.3075	GA	1.6318×10^7	156,000	15,697,000
			0.3081	DE	1.6364×10^7	170,264	15,651,000
			0.3221	PSO	1.7081×10^7	151,424	14,934,000
			0.3012	GSA	1.5984×10^7	152,928	16,031,000

Table 6
Percentage of active power loss reduction at different loading using GA, DE, PSO and GSA techniques in IEEE 30 bus system.

Evolutionary techniques	% Loss reduction for base loading	% Loss reduction for 110% of base loading	% Loss reduction for 120% of base loading
GA	75.12	66.50	54.23
DE	75.12	66.78	54.23
PSO	59.78	52.43	45.23
GSA	82.31	63.97	52.77

Table 7
Percentage of active power loss reduction at different loading using GA, DE, PSO and GSA techniques in IEEE 57 bus system.

Evolutionary techniques	% Loss reduction for base loading	% Loss reduction for 110% of base loading	% Loss reduction for 120% of base loading
GA	29.28	39.07	98.08
DE	29.11	39.07	97.70
PSO	22.98	32.11	89.10
GSA	23.52	40.72	75.94

Results and discussion

In this paper two types of FACTS devices namely TCSC (Thyristor Controlled Series Capacitor) and SVC (Static Var Compensator) are considered. First the location of FACTS devices are defined by calculating the power flow in the transmission lines. SVC's are connected at the buses 21, 17, 15 and 7 the finishing ends of the lines 27, 26, 18 and 9 respectively, since these are the four lines carrying highest, second highest, third highest and fourth highest reactive powers respectively. Then TCSC's positions are selected by choosing the lines carrying large reactive power. In IEEE 30 bus test system, lines 25, 41, 28 & 5 carry significant amount of reactive powers and are selected as candidate lines for the placement of Thyristor Controlled Series Capacitor. In IEEE-57 bus test system, four locations are selected for TCSC's and three locations are selected for SVC's. Lines 37th, 13th, 61st and 57th are found as the lines for TCSC placement and simultaneously series reactance of these lines are controlled. Bus number 49st, 25th and 38th are found as the candidate buses for the placement of SVC's. Here GA, DE, PSO and GSA based optimization techniques are applied on IEEE 30 and IEEE 57 bus system. GSA and other optimization techniques are used to determine optimum magnitudes of FACTS

Table 8
Active power flow and reactive power flow with FACTS devices under different loading in IEEE 30 bus system.

Location of generator	Generator connected with bus (E_b)	Line in between generator and the bus (E_b)	Methods	Active power flow between buses			Reactive power flow between buses			Phase angle between buses		
				Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)
2	4	3	GA	0.2916	0.3470	0.3888	0.0495	0.0165	−0.0266	0.0458	0.0553	0.0636
			DE	0.2921	0.3535	0.3981	0.0728	−0.0159	−0.1401	0.0448	0.0551	0.689
			PSO	0.2149	0.2587	0.2885	0.0146	−0.0931	−0.0431	0.0443	0.0517	0.0537
			GSA	0.2538	0.3123	0.3516	−0.1196	0.1059	−0.2599	0.0414	0.0491	0.0567
	5	5	GA	0.5852	0.6656	0.7520	0.0384	0.2069	0.1315	0.1101	0.1207	0.1364
			DE	0.5865	0.6582	0.7357	0.0383	0.2662	0.1760	0.1104	0.1146	0.1307
			PSO	0.8647	0.9753	1.1152	0.0384	0.0492	0.1202	0.1112	0.0722	0.0752
			GSA	0.7489	0.7744	0.8740	0.0502	0.1980	−0.0162	0.0792	0.0955	0.1094
	6	6	GA	0.3827	0.4535	0.5170	−0.0033	0.0137	−0.0393	0.0645	0.0744	0.0863
			DE	0.3835	0.4520	0.5239	0.0084	0.0061	−0.1821	0.0642	0.0732	0.0918
			PSO	0.2860	0.3442	0.3965	0.0071	−0.1388	−0.0872	0.0632	0.0705	0.0705
			GSA	0.3319	0.4168	0.4747	−0.1961	0.1244	−0.2555	0.0559	0.0667	0.0667
5	2	5	GA	−0.5852	−0.6656	−0.7520	−0.0384	−0.2069	−0.1315	−0.1101	−0.1207	−0.1364
			DE	−0.5865	−0.6582	−0.7357	−0.0383	−0.2662	−0.1760	−0.1104	−0.1146	−0.1307
			PSO	−0.8647	−0.9753	−1.1152	−0.0384	−0.0492	−0.1202	−0.1112	−0.0722	−0.0752
			GSA	−0.7489	−0.7744	−0.8740	−0.0502	−0.1980	−0.0162	−0.0792	−0.0955	−0.1094
	7	8	GA	−0.1264	−0.1591	−0.1711	0.0499	−0.0719	−0.0710	0.0168	−0.0163	−0.0166
			DE	−0.1252	−0.1635	−0.1763	0.0607	−0.1277	−0.2219	0.0172	0.0279	−0.0101
			PSO	0.1034	0.0988	0.1211	0.0806	−0.1969	−0.1816	0.0190	0.0095	0.0117
			GSA	0.0047	−0.0640	−0.2056	−0.2039	0.0322	−0.1526	0.0044	−0.0061	−0.0078
8	6	10	GA	0.0081	0.0081	0.0019	0.1918	−0.0379	−0.0004	0.0019	−0.0003	−0.0020
			DE	0.0076	0.0121	−0.0250	0.2414	−0.1581	0.4152	0.0011	−0.0013	−0.0071
			PSO	0.1266	0.0473	0.0453	0.2323	0.3944	0.3851	0.0041	−0.0022	−0.0020
			GSA	0.0257	0.0210	0.0193	−0.3057	−0.1819	0.0616	0.0031	0.0015	0.0021
	28	40	GA	0.0415	0.0135	−0.0129	0.0378	0.0055	0.0153	0.0057	0.0075	0.0069
			DE	0.0418	0.0127	0.0043	0.0463	−0.0203	0.1084	0.0088	0.0085	0.0022
			PSO	0.0721	−0.0420	−0.0736	0.0502	0.1668	0.1563	0.0039	−0.0192	−0.0248
			GSA	0.0122	0.0038	0.0065	0.2016	−0.0238	0.0229	0.0007	−0.0008	−0.0005
11	9	13	GA	0.1793	0.1709	0.1672	0.1433	0.2953	0.2835	0.0322	0.0288	0.0289
			DE	0.1793	0.1711	0.1669	0.1140	0.2150	0.0632	0.0320	0.0283	0.0292
			PSO	0.1750	0.1717	0.1683	−0.0634	0.4542	0.4605	0.0315	0.0246	0.0249
			GSA	0.1730	0.1717	0.0898	0.2316	0.4520	0.2502	0.0319	0.0323	0.0268
13	12	16	GA	0.1432	0.1590	0.1554	0.3766	0.2007	0.2204	0.0194	0.0185	0.0181
			DE	0.1390	0.1581	0.1544	0.4045	0.6201	0.4264	0.0192	0.0154	0.0162
			PSO	0.1642	0.1607	0.1579	0.0259	0.0511	0.0589	0.0193	0.0180	0.0195
			GSA	0.1624	0.1606	0.1563	0.0457	0.1132	0.4026	0.0226	0.0226	0.0198

* Sign is used to indicate multiplication operation.

Table 9
Active power flow and reactive power flow with FACTS devices under different loading in IEEE 57 bus system.

Location of generator	Generator connected with bus (E_b)	Line in between generator and the bus (E_b)	Methods	Active power flow between buses			Reactive power flow between buses			Phase angle between buses		
				Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)
2	3	2	GA	1.0153	1.4324	1.7292	−0.0044	0.0093	0.1103	0.0837	0.1153	0.1491
			DE	1.0014	1.3489	1.7488	−0.0045	−0.1889	0.4796	0.0837	0.01195	0.1450
			PSO	1.0161	1.3530	1.7650	−0.0048	−0.1891	0.0196	0.0839	0.1212	0.1549
			GSA	1.0213	1.3754	1.8632	0.1282	−0.1879	0.1601	0.1279	0.1223	0.1529
3	4	3	GA	0.6250	0.8774	1.1273	−0.0857	0.0997	0.2522	0.0240	0.0322	0.0430
			DE	0.6234	0.8759	1.1470	0.0839	0.02463	0.1468	0.0420	0.0296	0.0492
			PSO	0.6130	0.8599	1.1307	−0.0881	0.2028	0.3078	0.0237	0.0300	0.0440
			GSA	0.6266	0.9270	1.1260	0.2032	0.2858	0.7901	0.0340	0.0326	0.0426
	2	2	GA	−1.0153	−1.4324	−1.7292	0.0044	−0.0093	−0.1103	−0.0837	−0.1153	−0.1491
			DE	−1.0014	−1.3489	−1.7488	0.0045	0.1889	−0.4796	−0.0837	−0.1195	−0.1450
			PSO	−1.0161	−1.3530	−1.7650	0.0048	0.1891	−0.0196	−0.0839	−0.1212	−0.1549
			GSA	−1.0213	−1.3754	−1.8632	−0.1282	0.1879	−0.1601	−0.1279	−0.1223	−0.1529
6	4	5	GA	−0.1498	−0.2666	−0.3834	0.0292	−0.0210	−0.0936	−0.0232	−0.0465	−0.0681
			DE	−0.1515	−0.2593	−0.3985	0.0296	−0.1007	−0.0378	−0.0232	−0.0412	−0.0735
			PSO	−0.1453	−0.2641	−0.3787	0.0274	−0.0475	−0.0951	−0.0227	−0.0433	−0.0706
			GSA	−0.1418	−0.2856	−0.3820	0.1733	−0.0841	−0.3182	−0.0619	−0.0516	−0.0711
	7	6	GA	−0.1678	−0.1115	−0.0426	−0.0127	−0.0168	−0.0370	−0.0177	−0.0120	−0.0040
			DE	−0.1691	−0.1099	−0.0344	−0.0145	−0.0289	−0.0915	−0.0179	−0.0114	−0.0024
			PSO	−0.1742	−0.1100	−0.0441	−0.0021	0.0340	0.0027	−0.0185	−0.0126	−0.0033
			GSA	−0.1942	−0.0591	−0.0059	0.0241	0.1317	0.4013	0.0077	−0.0039	0.0016
	8	7	GA	−0.4366	−0.3860	−0.3179	−0.0417	−0.1508	−0.2225	−0.0742	−0.0651	−0.0545
			DE	−0.4363	−0.3838	−0.3090	−0.0417	−0.1581	−0.2963	−0.0742	−0.0641	−0.0533
			PSO	−0.4427	−0.3885	−0.3243	−0.0417	−0.1052	−0.1966	−0.0742	−0.0674	−0.0539
			GSA	−0.4347	−0.3987	−0.3312	−0.0293	−0.1531	0.4221	−0.0113	−0.0504	−0.0461
8	6	7	GA	0.4366	0.3860	−0.3179	0.0417	0.1508	0.2225	0.0742	0.0651	0.0545
			DE	0.4363	0.3838	−0.3090	0.0417	0.1581	0.2963	0.0742	0.0641	0.0533
			PSO	0.4427	0.3885	−0.3243	0.0417	0.1052	0.1966	0.0742	0.0674	0.0539
			GSA	0.4347	0.3987	−0.3312	0.0293	0.1531	−0.4221	0.0113	0.0504	0.0461
	9	8	GA	1.7773	1.6595	−0.3179	0.2288	0.6910	1.2047	0.0876	0.1117	0.0784
			DE	1.7742	1.6666	0.3090	0.2288	0.6522	1.4197	0.0877	0.0849	0.0764
			PSO	1.7731	1.6578	0.3243	0.2283	0.6231	1.2365	0.0880	0.0834	0.0764
			GSA	1.8216	1.5499	0.3312	0.8540	0.6409	−0.4433	0.0113	0.0588	0.0597
9	8	8	GA	−1.7773	−1.6595	−1.5065	−0.2288	−0.6910	−1.2047	−0.0876	−0.1117	−0.0784
			DE	−1.7742	−1.6666	−1.4805	−0.2288	−0.6522	−1.4197	−0.0877	−0.0849	−0.0764
			PSO	−1.7731	−1.6578	−1.4902	−0.2283	−0.6231	−1.2365	−0.0880	−0.0834	−0.0764
			GSA	−1.8216	−1.5499	−1.3922	−0.8540	−0.6409	0.4433	−0.0113	−0.0588	−0.0597
	10	9	GA	0.1695	0.1379	0.1001	−0.0879	0.0169	0.0677	0.0318	0.0273	0.0194
			DE	0.1699	0.1380	0.0963	−0.0860	0.0184	0.1290	0.0319	0.0270	0.0164
			PSO	0.1667	0.1428	0.1009	−0.0816	0.0237	0.1090	0.0333	0.0211	0.0210
			GSA	0.1641	0.1274	0.1170	−0.0130	−0.0736	−0.2100	−0.0148	0.0201	0.0185
	11	10	GA	0.1365	0.0575	−0.0118	−0.0329	0.0170	0.0129	0.0127	0.0050	−0.0028
			DE	0.1377	0.0596	−0.0189	−0.0279	0.0088	0.0703	0.0127	0.0054	0.0048
			PSO	0.1374	0.0419	−0.0341	−0.0613	0.0077	0.0196	0.0133	0.0040	−0.0068
			GSA	0.1268	0.0465	−0.0455	−0.2477	0.0792	−0.6476	−0.0209	−0.0037	−0.0113
	12	11	GA	0.0286	−0.0049	−0.0353	−0.1213	−0.0808	−0.0274	0.0152	0.0053	−0.0119
			DE	0.0272	−0.0034	−0.0425	−0.1213	−0.0759	0.0223	0.0153	0.0053	−0.0195
			PSO	0.0284	−0.0026	−0.0355	−0.1218	−0.0712	0.0236	0.0189	0.0044	−0.0186
			GSA	0.0188	−0.0101	−0.0409	0.0054	−0.1489	−0.0867	−0.0479	−0.0046	−0.0117
	13	12	GA	0.0232	−0.0600	−0.1347	−0.0722	−0.0548	−0.0772	0.0070	−0.0085	−0.0253
			DE	0.0213	−0.0583	−0.1428	−0.0707	−0.0649	−0.0255	0.0068	−0.0076	−0.0292
			PSO	0.0228	−0.0575	−0.1386	−0.0809	−0.0317	−0.0350	0.0078	−0.0094	−0.0331
			GSA	−0.0049	−0.0908	−0.1830	−0.2079	−0.0359	−0.5832	−0.0497	−0.0235	−0.0417
	55	80	GA	0.1476	0.1511	0.1448	−0.7389	−0.6444	−0.5190	0.0172	0.0203	0.0225
			DE	0.1476	0.1520	0.1431	−0.7377	−0.6477	−0.4858	0.0172	0.0203	0.0314
			PSO	0.1479	0.1522	0.1454	−0.2803	−0.6510	−0.5174	0.0184	0.0207	0.0222
			GSA	0.2250	0.1290	0.1274	−0.1133	0.4008	−0.3069	0.0053	0.0153	0.0198
12	9	11	GA	−0.0286	0.0049	0.0353	0.1213	0.0808	0.0274	−0.0152	−0.0053	0.0119
			DE	−0.0272	0.0034	0.0425	0.1213	0.0759	−0.0223	−0.0153	−0.0053	0.0195
			PSO	−0.0284	0.0026	0.0355	0.1218	0.0712	−0.0236	−0.0159	−0.0044	0.0186
			GSA	−0.0188	0.0101	0.0409	−0.0054	0.1489	0.0867	0.0479	0.0046	0.0117

(continued on next page)

Table 9 (*continued*)

Location of generator	Generator connected with bus (E_b)	Line in between generator and the bus (E_b)	Methods	Active power flow between buses			Reactive power flow between buses			Phase angle between buses		
				Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)	Base (Pd, Qd)	1.10* (Pd, Qd)	1.20* (Pd, Qd)
	10	23	GA	0.1642	0.1999	0.2156	0.1632	0.2092	0.1523	0.0166	0.0220	0.0313
			DE	0.1688	0.1959	0.2225	0.1655	0.1988	0.1169	0.0166	0.0217	0.0359
			PSO	0.1598	0.2004	0.2136	0.1720	0.1957	0.0887	0.0174	0.0167	0.0396
			GSA	0.1814	0.2028	0.2520	0.0035	0.2519	0.0858	0.0331	0.0247	0.0302
	13	25	GA	−0.0443	0.1084	−0.1813	0.4305	0.2568	−0.0885	−0.0082	−0.0138	−0.0134
			DE	−0.0373	−0.1136	−0.1811	0.4347	0.2039	−0.1953	−0.0085	0.0129	−0.0097
			PSO	−0.0511	−0.1167	−0.2048	0.4094	0.2723	−0.2248	−0.0081	−0.0138	−0.0145
			GSA	−0.0624	−0.1401	−0.2785	0.5771	0.6687	−1.1523	−0.0018	−0.0189	−0.0270
	16	26	GA	−0.3334	−0.5073	−0.6460	0.0961	0.0660	−0.2505	−0.0292	−0.0447	−0.0615
			DE	−0.3423	−0.5004	−0.6424	0.0962	−0.0634	−0.3341	−0.0275	−0.0441	−0.0619
			PSO	−0.3256	−0.5024	−0.6253	0.0964	−0.0641	−0.2971	0.0275	−0.0438	−0.0633
			GSA	−0.3431	−0.5126	−0.6155	−0.6780	0.0086	−1.2483	−0.0399	−0.0436	−0.0600
	17	27	GA	−0.4632	−0.9892	−0.8560	0.1130	0.0925	−0.2855	−0.0888	−0.1322	−0.1740
			DE	−0.4717	−0.6819	−0.8528	0.1131	−0.0898	−0.3714	−0.0871	−0.1308	−0.1693
			PSO	−0.4557	−0.6840	−0.8337	0.1136	−0.0906	−0.3342	−0.0873	−0.1303	−0.1784
			GSA	−0.4725	−0.6946	−0.8249	−0.5317	−0.0163	−0.9740	−0.1173	−0.1293	−0.1705

* Sign is used to indicate multiplication operation.

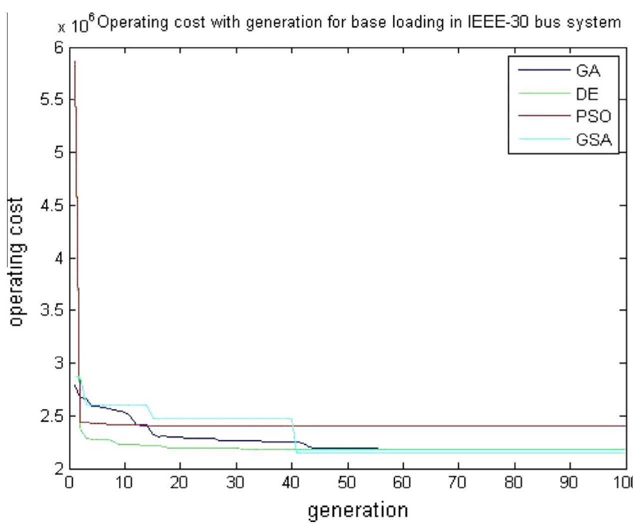

Fig. 6. Variation of operating cost with generation for base loading using GA, DE, PSO and GSA for IEEE 30 bus system.

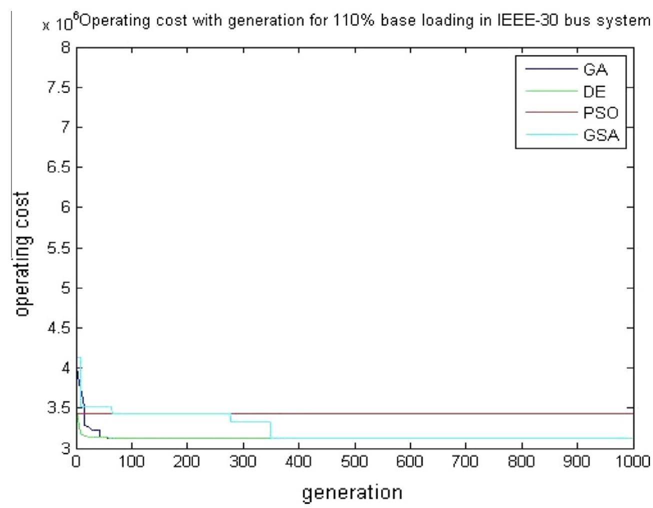

Fig. 7. Variation of operating cost with generation for 110% of base loading using GA, DE, PSO and GSA for IEEE 30 bus system.

devices placed at different locations already defined and system performance is observed without and with FACTS devices. Tables 1 and 2 shows the locations of different FACTS devices in the transmission lines in IEEE 30 and IEEE 57 bus systems. Table 3 shows the total reactive power loss of the system without and with FACTS devices. A comparative study of the operating cost of the system without and with FACTS devices using GA, DE, PSO and GSA technique under different loading conditions are shown in Table 4 for IEEE 30 bus system and Table 5 for IEEE 57 bus system. Tables 6 and 7 shows comparative study of the percentage loss reduction without and with FACTS devices using GA, DE, PSO and GSA technique under different loading conditions for both the systems respectively.

From Table 3, it is observed that after installation of FACTS devices in the pre-defined location, the sum of reactive power flow of all lines reduces considerably. The decrease is more in case of GSA based optimization algorithm.

It has been observed that operating cost and active power loss using GA, DE, PSO and GSA algorithms is reduced significantly in all cases of loading with FACTS devices as well as significant economic gain is obtained. The economic gain obtained is much higher than the installation cost of FACTS devices in all cases of loading.

The loss reduction is calculated on the basis of the loss occurred without and with FACTS devices for 100%, 110% and 120% of base loading conditions. Hence it is clear from the Tables 6 and 7 that optimal placement of FACTS devices in the systems can effectively reduce the transmission loss of the system. GSA method can be an effective method for the planning of FACTS devices in reducing active power loss and reactive power flow in all the congested lines. Effect of FACTS devices on the active power flow, reactive power flow and the phase angle in lines connected between generator bus and load bus is shown in Tables 8 and 9 for both the systems with proposed approach. From the results, as observed from Tables 8 and 9, it is clear that each generator in both IEEE 30 and IEEE 57 bus test systems are being able to transfer significant amount of active powers through the lines connected to other load buses. Similarly, there is considerable reduction of reactive power flow in these lines. This phenomenon is found to be true for all cases of increased loading condition.

Variations of operating cost with generation using GA, DE, PSO and GSA techniques under different loading conditions for IEEE-30 bus test system are shown in Figs. 6–8. Similarly, Figs. 9–11 shows variation of operating cost with generation using GA, DE, PSO and

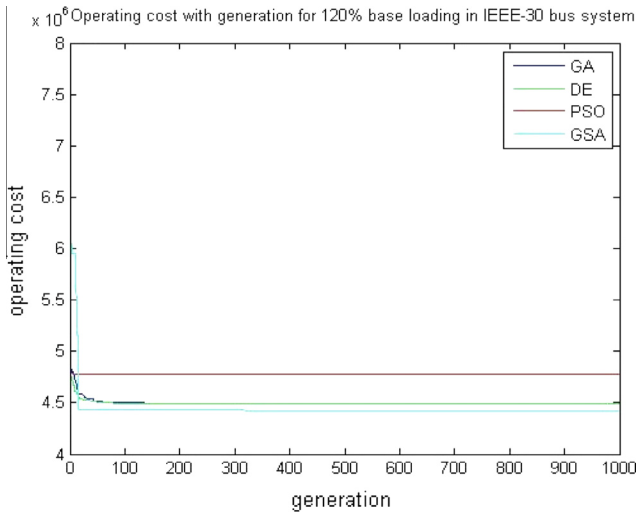

Fig. 8. Variation of operating cost with generation for 120% of base loading using GA, DE, PSO and GSA for IEEE 30 bus system.

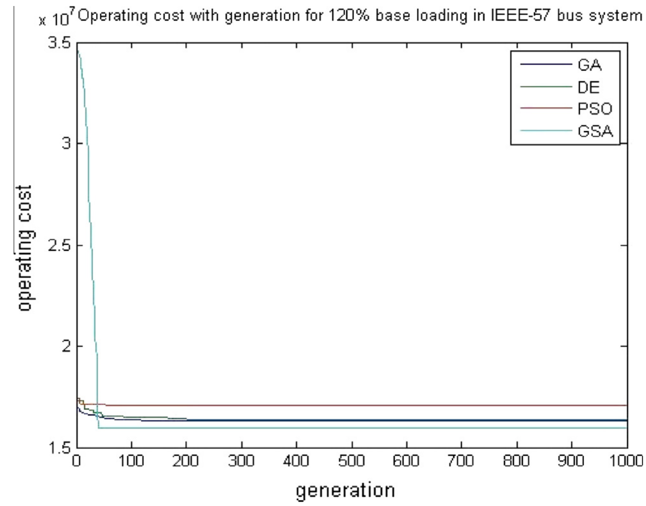

Fig. 11. Variation of operating cost with generation for 120% of base loading using GA, DE, PSO and GSA for IEEE 57 bus system.

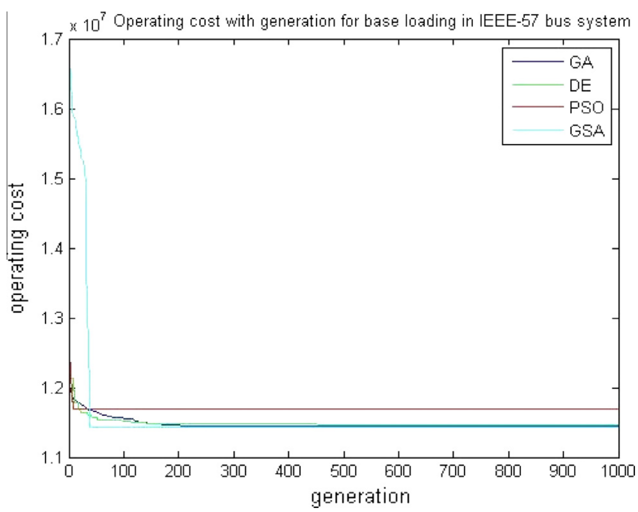

Fig. 9. Variation of operating cost with generation for base loading using GA, DE, PSO and GSA for IEEE 57 bus system.

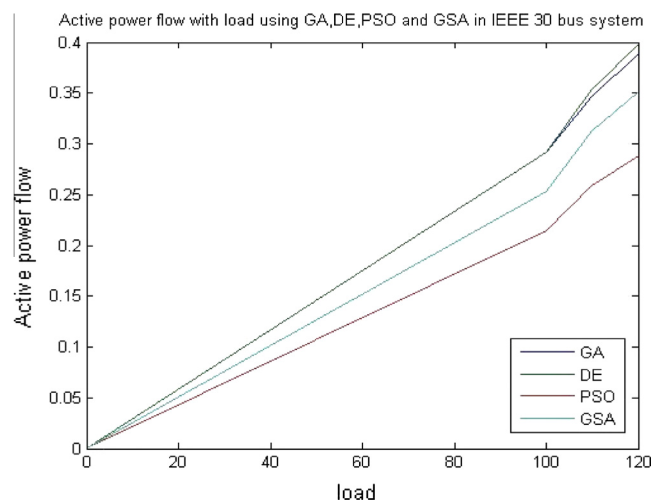

Fig. 12. Active power flow with active and reactive loading for generator 2 connected to bus 4.

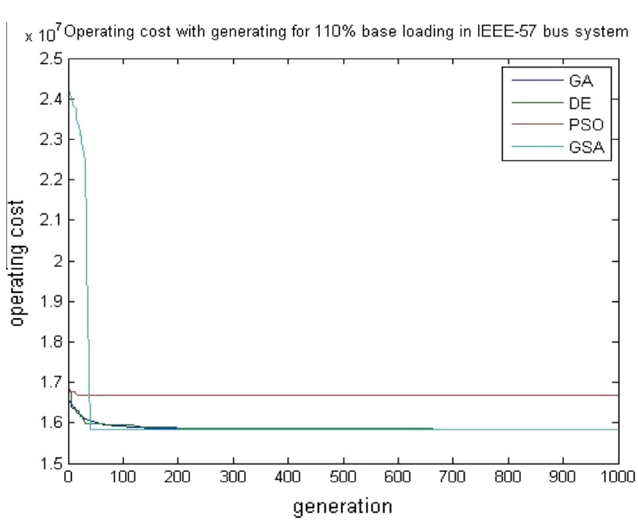

Fig. 10. Variation of operating cost with generation for 110% of base loading using GA, DE, PSO and GSA for IEEE 57 bus system.

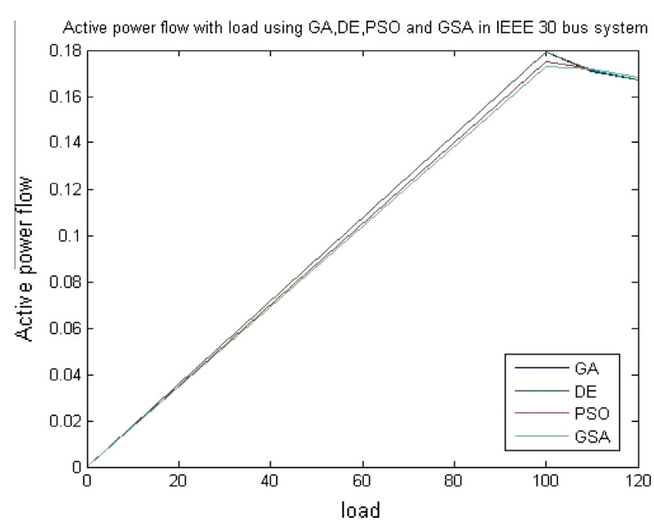

Fig. 13. Active power flow with active and reactive loading for generator 11 connected to bus 9.

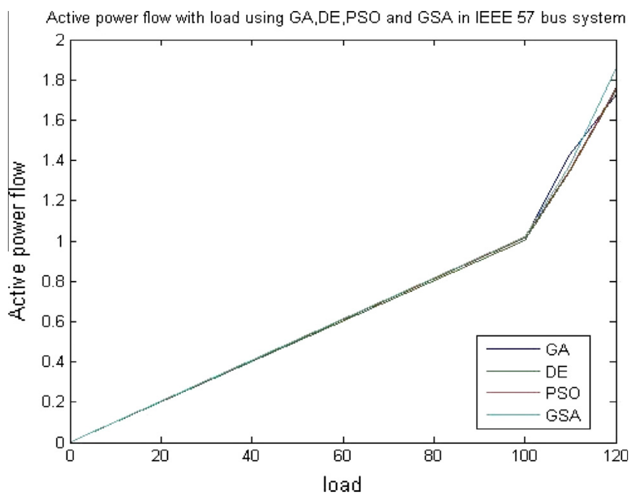

Fig. 14. Active power flow with active and reactive loading for generator 2 connected to bus 3.

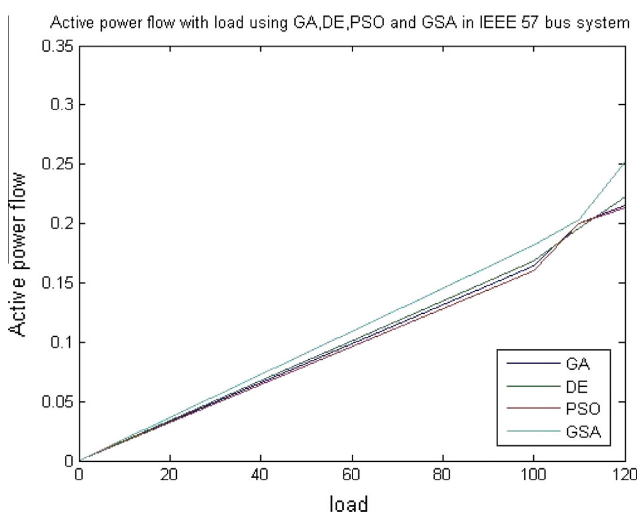

Fig. 15. Active power flow with active and reactive loading for generator 12 connected to bus 10.

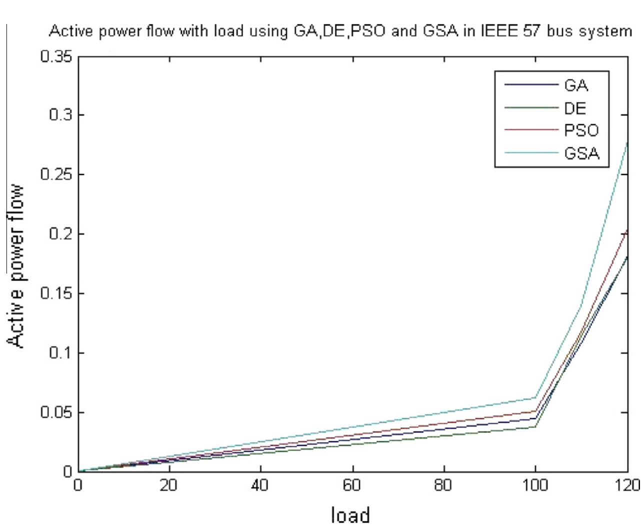

Fig. 16. Active power flow with active and reactive loading for generator 12 connected to bus 13.

GSA techniques for IEEE-57 bus test system under different cases of loadings. Optimization algorithms are run for 100 generations and number of populations are taken as 80 for IEEE-30 bus system. For IEEE-57 bus system, optimization algorithms are run for 200 generations as number of string variables are more in 57 bus system compared to 30 bus system. The number of populations are taken as 80 as in 30 bus system.

Effect of FACTS devices on some selected generator buses are shown by, Figs. 12 and 13 for IEEE 30 bus test system. Similarly effect of FACT devices on some generator buses of IEEE 57 bus test system is shown in Figs. 14–16.

Conclusion

In this paper the usefulness of GA, DE, PSO and GSA based optimal placement of FACTS devices in a transmission network is tested for the increased loadability of the power system as well as to minimize the total operating cost and total active power loss. Results showed that the proposed GSA algorithm is efficient for reduction of power losses, improvement of the voltage profile as well as reduction of total operating cost maintaining all the constraints. From the convergence characteristics of operating cost with iteration for different optimization techniques, it is found that GSA is the best among all the methods. It gives minimum operating cost and active power loss among all the methods. Furthermore, the effect of FACTS devices on transfer capability of each generator present in the transmission system is investigated and it is found that even at increased loading condition, generators are being able to dispatch significant amount of active power without increasing steam flow rate corresponding to the base loading situation. This is the significant contribution of FACTS (Flexible AC Transmission System) devices when both active & reactive loading is considered though it is obvious that FACTS devices is able to inject large amount of reactive power into the system under only reactive loading cases. Hence, key issue is the optimum co-ordination of FACTS (Flexible AC Transmission System) devices with the existing reactive power sources for achieving all the mentioned benefits. Here, in the proposed work, the result shows that GSA can be a proper optimization algorithm for optimal planning of FACTS devices for the enhancement of loadability of the power system.

References

[1] Hingorani N. Flexible AC transmission. IEEE Spect 1993;30(4):40–5.

[2] Wang X, Song YH, Lu Q. Lagrangian decomposition approach to active power congestion management across interconnected regions. IEE Proc Gen, Trans Dis 2001;148(5):497–503.

[3] Mohamed Shuaib Y, Surya Kalavathi M, Christober Asir Rajan C. Optimal reconfiguration in radial distribution system using gravitational search algorithm. Electr Power Comp Syst 2014;42(7):703–15.

[4] Lie TT, Deng W. Optimal flexible AC Transmission systems (FACTS) devices allocation. Int J Electr Power Energy Syst 1997;19(2):125–34.

[5] Ibrahim E, Abusorrah A. Optimal allocations of SVCs for improvement of power system performance. Electr Power Comp Syst 2003;31(1):27–46.

[6] Acharya Naresh, Mithulananthan N. Locating series FACTS devices for congestion management in deregulated electricity markets. Electr Power Syst Res 2007;77(3–4):352–60.

[7] Besharat Hadi, Taher Seyed Abbas. Congestion management by determining optimal location of TCSC in deregulated power systems. Int J Electr Power Energy Syst 2008;30(10):563–8.

[8] Colvara LD, Araujo SCB, Festraits EB. Stability analysis of power system including facts (TCSC) effects by direct method approach. Int J Electr Power Energy Syst 2005;27:264–74.

[9] Abdelaziz AY, EL-Sharkawy MA, Attia MA. Optimal location of thyristor-controlled series compensators in power systems for increasing loadability by genetic algorithm. Electr Power Comp Syst 2011;39(13):1373–87.

[10] Nelson R, Bian J, Williams S. Transmission series power flow control. IEEE Trans Power Deliv 1995;10(1):504–10.

[11] Padhy Narayana Prasad, Abdel Moamen MA. Power flow control and solutions with multiple and multi-type FACTS devices. Electr Power Syst Res 2005;74:341–51.

[12] Xiao Y, Song YH, Liu Chen-Ching, Sun YZ. Available transfer capability enhancement using FACTS devices. IEEE Trans Power Syst 2003;18(1):305–12.

[13] Xiao Y, Song YH, Sun YZ. Power flow control approach to power systems with embedded FACTS devices. IEEE Trans Power Syst 2002;17(4):943–50.
[14] Kumar Ashwani, Sekhar Charan. Congestion management with FACTS devices in deregulated electricity markets ensuring loadability limit. Int J Electr Power Energy Syst 2013;46:258–73.
[15] Yousefi A, Nguyen TT, Zareipour H, Malik OP. Congestion management using demand response and FACTS devices. Int J Electr Power Energy Syst 2012;37(1):78–85.
[16] Preedavichit P, Srivastava SC. Optimal reactive power dispatch considering FACTS devices. Int J Electr Power Syst Res 1998;46(3):251–7.
[17] Gotham DJ, Heydt GT. Power flow control and power flow studies for system with FACTS devices. IEEE Trans Power Syst 1998;13:60–5.
[18] Chung TS, Li YZ. A hybrid GA approach for OPF with consideration of FACTS devices. IEEE Power Eng Rev 2000;August:54–7.
[19] Gerbex S, Cherkaoui R, Germond AJ. Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms. IEEE Trans Power Syst 2001;16(3):537–44.
[20] Cai LJ. Optimal choice and allocation of FACTS devices in deregulated electricity market using genetic algorithms. In: IEEE PES, 2004. p. 56.
[21] Alhasawi FB, Milanovic JV. Techno-economic contribution of FACTS devices to the operation of power systems with high level of wind power integration. IEEE Trans Power Syst 2012;27(3):1414–21.
[22] Verma KS, Singh SN, Gupta HO. Location of unified power flow controller for congestion management. Electr Power Syst Res 2001;58(2):89–96.
[23] Hajforoosh S, Nabavi SMH, Masoum MAS. Coordinated aggregated-based particle swarm optimisation algorithm for congestion management in restructured power market by placement and sizing of unified power flow controller. IET Sci Meas Technol 2012;6(4):267–78.
[24] Duman S, Sonmez Y, Guvenc U, Yorukeren N. Optimal reactive power dispatch using a gravitational search algorithm. IET Gen Trans Distrib 2012;6(6):563–76.
[25] Duman Serhat, Guvenc Ugur, Sonmez Yusuf, Yorukeren Nuran. Optimal power flow using gravitational search algorithm. Energy Conver Manage 2012;59:86–95.
[26] Nagalakshmi S, Kamaraj N. Comparison of computational intelligence algorithms for loadability enhancement of restructured power system with FACTS devices. Swarm Evol Comput 2012;5(August):17–27.
[27] Phichaisawat S, Song YH, Wang XL, Wang XF. Combined active and reactive congestion management with FACTS devices. Electr Power Comp Syst 2002;30(12):1195–205.
[28] Vlachogiannis John G. FACTS applications in load flow studies effect on the steady state analysis of the Hellenic transmission system. Electr Power Syst Res 2000;55(September):179–89.