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Comparative study of GA & DE algorithm for the economic operation of a power system using FACTS devices

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Abstract: The problem of improving the voltage profile and reducing power loss in electrical networks must be solved in an optimal manner. This paper deals with comparative study of Genetic Algorithm (GA) and Differential Evolution (DE) based algorithm for the optimal allocation of multiple FACTS (Flexible AC Transmission System) devices in an interconnected power system for the economic operation as well as to enhance loadability of lines. Proper placement of FACTS devices like Static VAr Compensator (SVC), Thyristor Controlled Switched Capacitor (TCSC) and controlling reactive generations of the generators and transformer tap settings simultaneously improves the system performance greatly using the proposed approach. These GA & DE based methods are applied on standard IEEE 30 bus system. The system is reactively loaded starting from base to 200% of base load. FACTS devices are installed in the different locations of the power system and system performance is observed with and without FACTS devices. First, the locations, where the FACTS devices to be placed is determined by calculating active and reactive power flows in the lines. GA and DE based algorithm is then applied to find the amount of magnitudes of the FACTS devices. Finally the comparison between these two techniques for the placement of FACTS devices are presented.

Key words: FACTS devices, line power flow, FACTS devices & its optimal locations, genetic algorithm, differential evolution technique

Nomenclature

R_{Line} – Resistance of line; X_{Line} – Reactance of line; Z_{Line} – Line Impedance; X_{ij} – Reactance between i^{th} & j^{th} node; X_{TCSC} – Reactance of TCSC; G_{TCSC} – Real part of Admittance of TCSC; B_{TCSC} – Imaginary part of Admittance of TCSC; r_{TCSC} – Coefficient which represents the compensation degree of TCSC; X_C – Capacitive reactance of SVC reactor bank; X_L – Inductive reactance of SVC reactor bank; $á$ – Firing angle of SVC; X_{SVC} – Reactance of SVC; S – Operating range of FACTS devices; C_{TOTAL} – Total cost of system operation; C_1 (E) – Cost due to energy loss; C_2 (F) – Total investment cost of the FACTS Devices; $p_{ni}^{\min}$, $p_{ni}^{\max}$ Lower and Upper limit of nodal active power in the i^{th} bus respectively; P_{ni}, Q_{ni} – Nodal active and reactive power output of the i^{th} bus respectively; $Q_{ni}^{\min}$, $Q_{ni}^{\max}$ – Lower and Upper limit of nodal reactive power in the i^{th} bus respectively; $Q_{gi}^{\min}$ $Q_{gi}^{\max}$ – Lower and Upper limit of existing nodal reactive capacity in the i^{th} bus respectively; Q_{gi} – Output of existing nodal reactive capacity in the i^{th} bus; P_{Gi}, Q_{Gi} – Active and Reactive power generation in the i^{th} bus respectively; P_{Di}, Q_{Di} – Active and Reactive power consumed by load in the i^{th} bus respectively; P_i, $Q_{i(\text{inj})}$ – Real and reactive power flow change takes place at the node i due to TCSC connected to a particular line between the nodes i & j; $Q_{iL(\mathrm{inj})}$ – Reactive power injection due to SVC; V_i, V_j – Voltage of i^{th} and j^{th} bus respectively; N – Number of lines; G_{ij}, B_{ij} – Real and Imaginary part of admittance between buses i & j respectively; θ_{ij}– Phase angle between V_i & V_j

1. Introduction

Transmission lines are often driven close to or even beyond their thermal limits in order to satisfy the increased electric power consumption and trades due to increase of the unplanned power exchanges. Environmental right-of-way and cost problems are major hurdles for power transmission network expansion. Hence there is an interest in better utilization of the existing power system capabilities. Thus the existing transmission lines are overloaded which leads to unstable system. With the development of power electronics, FACTS devices have been proposed and implemented in power systems. The benefits about FACTS devices include improvement of system dynamic behavior and enhancement of system stability. It is known that the power flow through an ac transmission line is a function of line impedance, the magnitude and the phase angle between the sending and the receiving end voltages. By proper coordination of FACTS devices in the power system network, it is used to reduce the flows in heavily loaded lines, resulting in an increased loadability and low system loss. Reactive power flow control and the increased use of transmission capacity by FACTS devices are discussed in [1]. A scheme of power flow control in lines is discussed in [2]. The system load ability and loss minimization are used as an objective function. Use of static phase shifters and FACTS controllers to increase the power transfer capacity in the transmission line is described in [3, 4]. A simple approach based on the optimal location of FACTS devices are discussed in [5]. Modeling and optimum location of variable FACTS devices are discussed in [6, 7]. Power injection model of FACTS devices and Optimal Power Flow (OPF) model is discussed in [8, 9] which present a novel power flow control approach to enable the working of different FACTS devices. Assessment and Impact of FACTS devices on power networks have been discussed in [10] through the concept of steady state security regions. The placement of different FACTS devices in a power system using Genetic Algorithm is discussed [11]. The system load ability is carried out to measure power system performance. In [12] authors have discussed about the most important feature of the TCSC i.e. its variable degree of compensation that can be used in damping out low-frequency oscillations, controlling the power flow, etc. A hybrid Genetic Algorithmic approach with FACTS devices for optimal power flow is dealt in [13]. In [14] an adaptive stabilizer design for SVC control in power systems for either voltage regulation or controlling dynamic and transient performance under abnormal condition is discussed. Steady state firing angle model of SVC and TCSC for power flow solution were developed and discussed in [15]. SVC and TCSC are capable of controlling voltage magnitude, phase angle and line reactance. By controlling these parameters we can control reactive power flow and minimize transmission loss. Minimization of transmission loss is a problem of reactive power optimization and can be done by controlling reactive generations of the generators, controlling transformer tap positions and adding shunt capacitors in the weak buses [16] but the active power flow pattern can not be controlled. A GA based approach is presented in [17] to determine the optimal location and rating of the FACTS devices in power system. Power flow control with different FACTS devices were discussed in [18]. DE based algorithmic approach using FACTS devices for the minimization of generator fuel cost is discussed in [19].

In the proposed work, first the locations of the FACTS devices are identified by calculating different line flows. TCSC's are placed in lines where reactive power flows are very high and the SVC's are connected at the receiving end buses of the other lines carrying significant amount of reactive power. The objective of this paper is to develop an algorithm to find optimal locations for the FACTS devices by calculating different line flows. A comparative study is made between GA and DE approach to calculate the overall cost, which includes the cost occurred due to transmission loss and the investment costs of FACTS devices at different loading conditions.

2. FACTS devices

A) Modelling of FACTS Devices

For the steady state analysis it is necessary to model the FACTS devices mathematically. Thyristor controlled swithced capacitors (TCSC) and Static VAr Compensators (SVC) are used as FACTS devices in the transmission network in this approach.

TCSC

TCSC acts as either inductive or capacitive compensator by changing the line reactance. The maximum value of the capacitance is fixed at –0.8 X_L and 0.2X_L is the maximum value of the inductance, where X_L is the line reactance. When a TCSC is connected to a particular line, its admittance can be written as

$$G_{\mathrm{TCSC}} + jB_{\mathrm{TCSC}} = \frac{1}{R_{\mathrm{Line}} + j(X_{\mathrm{Line}} + X_{\mathrm{TCSC}})}, \tag{1}$$

TCSC allows faster changes of transmission line impedance. Figure 1 shows the mathematical model of TCSC connected with transmission lines.

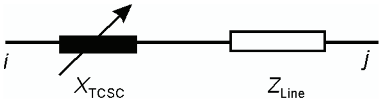

Fig. 1. Mathematical model of TCSC

$Z_{\mathrm{Line}} = R_{\mathrm{Line}} + jX_{\mathrm{Line}}$,
$X_{ij} = X_{\mathrm{Line}} + X_{\mathrm{TCSC}}$,
$X_{\mathrm{TCSC}} = r_{\mathrm{TCSC}} \times X_{\mathrm{Line}}$.

SVC

SVC can be considered as to generate or absorb controllable reactive power by synchronously switching capacitor and reactor banks "in" and "out" of the network. The main function of SVC is to absorb reactive power from the bus or to inject reactive power to the bus where it is installed. The SVC's effective reactance X_{SVC} is determined by parallel combination of X_C & X_L and is given by

$$X_{\mathrm{SVC}} = \frac{\pi X_C X_L}{X_C[2(\pi - \alpha) + 2\sin\alpha] - \pi X_L}. \tag{2}$$

The SVC model is shown in Figure 2.

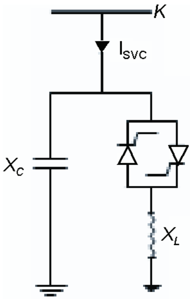

Fig. 2. SVC firing angle model

B) FACTS Devices cost Functions

According to [20], cost function of TCSC and SVC are given as:

TCSC:

$$C_{\mathrm{TCSC}} = 0.0015\mathrm{S}^2 - 0.7130\mathrm{S} + 127.38 \text{ (US \$/kVar)}, \tag{3}$$

SVC:

$$C_{\mathrm{SVC}} = 0.0003\mathrm{S}^2 - 0.2691\mathrm{S} + 188.22 \text{ (US \$/kVar)}. \tag{4}$$

3. Problem formulation

The main objective of this paper is to minimize the transmission loss by installing FACTS devices at the optimal locations of the transmission network. Placement of FACTS controllers also increase the system cost as the cost of the FACTS devices are also to be taken into consideration. So, optimal placement of FACTS devices is required such that the gain obtained by reducing the transmission loss is significant even after the placement of costly FACTS devices. Installation costs of various FACTS devices and the cost of system operation, namely, energy loss cost are combined to form the objective function to be minimized. The optimal allocation of FACTS devices can be formulated as:

$$C_{\mathrm{TOTAL}} = C_1(E) + C_2(F). \tag{5}$$

Subject to the nodal active and reactive power balance

$$P_{ni}^{\min} \le P_{ni} \le P_{ni}^{\max},$$

$$Q_{ni}^{\min} \le Q_{ni} \le Q_{ni}^{\max},$$

voltage magnitude constraints: $V_i^{\min} \le V_i \le V_i^{\max}$ and the existing nodal reactive capacity constraints:

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}.$$

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

The power flow equations between the nodes $i - j$ after incorporating FACTS devices would appear as

TCSC:

$$P_{Gi} - P_{Di} + P_i - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0, \tag{6}$$

$$Q_{Gi} - Q_{Di} + Q_{i(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0, \tag{7}$$

$$P_{Gj} - P_{Dj} + P_i - \sum_{j=1}^{N-1} V_j V_j (G_{jj}\cos\theta_{jj} + B_{jj}\sin\theta_{jj}) = 0, \tag{8}$$

$$Q_{Gj} - Q_{Dj} + Q_{j(inj)} - \sum_{j=1}^{N-1} V_j V_j (G_{jj}\sin\theta_{jj} - B_{jj}\cos\theta_{jj}). \tag{9}$$

SVC:

$$Q_{Gj} - Q_{Dj} + Q_{j(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0. \tag{10}$$

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 both in the cases of Genetic Algorithm and Differential Evolution based approaches.

4. Optimal placement of FACTS devices using evolutionary technique

The optimization problem includes basically three aspects: finding the optimal location of the device in the network, finding its optimal size, and optimizing its controller parameters such that the maximum benefit can be obtained. Placement of FACTS devices depends upon the characteristics of the specific system as SVC's are mostly suitable when reactive power flow or voltage support is necessary. FACTS devices are placed in the more heavily loaded lines to limit the power flow in that line. This causes more power to be sent through the remaining portions of the system while protecting the line with the device for being overloaded. If reactive power flow is a significant portion of the total flow on the limiting transmission line, either a TCSC device in the line or a SVC device located at the end of the line that receives the reactive power, may be used to reduce the reactive power flow, thereby increasing the active power flow capacity.

In this approach, first the locations of FACTS devices are defined by calculating the power flow in the transmission lines. SVC positions are selected by choosing the lines carrying largest reactive power. Here we choose only eight locations for the placement of FACTS devices. The 21st, 7th, 17th & 15th buses found as the buses where suitable reactive injection by SVC could improve the system performance. Lines 25, 41, 28 & 5 found as the lines for TCSC placement and simultaneously series reactance of these lines are controlled.

Genetic algorithm in the proposed method

The function of the GA is to find the optimum value of the different FACTS devices. Here two different types of FACTS devices are used. And for each type of FACTS devices, four positions are assigned. Four TCSC modifies reactance of four lines. Similarly four SVC's are to control reactive injection at four buses. In addition transformer tap positions along with reactive generations of the Generators are controlled. In IEEE 30 bus system there are four tap positions and five Generator Buses. So, as a whole seventeen values are to be optimized by Genetic Algorithm [21]. These seventeen controlling parameters are represented with in a string. This is shown in Figure 3. Initially a population of N strings is randomly created in such a way so that the parameter values should be within their limits. Then the objective function is computed for every individual of the population. A biased roulette wheel is created from the values obtained after computing the objective function for all the individuals of the current population. Thereafter the usual Genetic operation such as Reproduction, Cross-over & Mutation takes place. Two individuals are randomly selected from the current population for reproduction. Then cross-over takes place with a probability close to one (here 0.8). Finally mutation with a specific probability (very low) completes one Genetic cycle and individuals of same population with improved characters are created in the next generation. The objective function is then again calculated for all the individual of the new generation and all the genetic operations are again performed and the second generation of same population size is produced. This procedure is repeated till the final goal is achieved.

Differential evolution technique in brief

Differential Evolution (DE) developed by Storm & Price [22] is very similar to GA in the sense that it also uses the cross-over, mutation and the selection procedure in a different way than performed in the GA. Initial populations are created randomly that are represented by strings where the variables inside string are same as that of GA which is shown in Figure 3. In DE each vector in the population becomes a target vector. Each target vector is combined with a donor vector and a random vector differential in order to produce a trial vector. If the cost of the trial vector is less than the target, the trial vector replaces the target in the next generation. The donor vector is selected such that its cost is either less than or equal to the target vector. Mutation in GA is generally performed by generating a random value utilizing a predefined probability density function. In DE the differential vector, where the contributors are the target, the donor and two other randomly selected vectors perform the mutation. The objective function is calculated for all the individual of the new generation and the procedure is repeated till the final goal is achieved.

TCSC	SVC	Transformer tap	Reactive generations of generators
4 Nos.	4 Nos.	4 Nos.	5 Nos.

Fig. 3. String representing the control variables

5. Test results and discussion

The proposed GA & DE based evolutionary technique has been implemented on IEEE 30-bus system for different loading conditions. FACTS devices are placed at the optimal location and system performance is observed with and without FACTS devices. Table 1 shows the locations of different FACTS devices in the transmission network. Table 2 shows the comparative analysis of active power loss using GA & DE approach. Table 3 shows the reactive power flow pattern without and with FACTS devices in lines before and after placement of FACTS devices at different loading conditions using GA & DE based approach. The magnitude and phase angle of the bus voltages after placement of SVC with & without FACTS devices by GA and DE algorithm for highest reactive loading i.e. for 200% is shown in Table 4. Phase angles are given in radian. Amount of FACTS devices, reactive generations of the generators and transformer tap positions in different cases of loading is shown in Table 5 & 6 using GA & DE approach. A comparative study of the operating cost of the system with and without FACTS devices using GA & DE is given in Table 7. It is observed from Table 1, that SVC's are connected at the buses 21, 7, 17 & 15, the finishing ends of the lines 27, 26, 9 & 18 respectively, since these are the four lines carrying highest, second highest, third & fourth highest reactive power respectively, without FACTS devices. After connecting SVC's at theses buses, voltage profile at these buses are improved, also reactive power flow reduces in large amount in the lines 27, 26, 9, 18 in all cases of loading. TCSC's are placed in the lines 5, 18, 25 & 41, as these are the next four highest reactive powers. It is also to be noticed that no FACTS device is connected in line 1 because of the reason that it is in between bus 1 and bus 2 though it carries very large active power. Bus 1 is the slack bus and already a FACTS device regulates the voltage of the bus 2. Again in any line or in a bus connected with the line, only one FACTS device can be placed. From table 2 it is clear that the active power loss occurred after applying GA & DE technique is almost same at different loading conditions.

Table 1. Locations of different FACTS devices in the transmission network

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

Table 2. Comparative analysis of active power loss using GA & DE approach

Reactive loading	**Active power loss without FACTS (p.u)**	**Active power loss with FACTS using GA (p.u)**	**Active power loss with FACTS using DE (p.u)**
100%	0.0711	0.0406	0.0406
150%	0.0742	0.0433	0.0434
175%	0.0765	0.0448	0.0458
200%	0.0795	0.0573	0.0576

Table 3. Comparative study of reactive power flow in line with GA & DE

Lines	**For base reactive loading of 150% (before) in p.u**	**For base reactive loading of 150% (by the GA based approach) in p.u**	**For base reactive loading of 150% (by the DE based approach) in p.u**	**For reactive loading of 200% (before) in p.u**	**For base reactive loading of 200% (by the GA based approach) in p.u**	**For base reactive loading of 200% (by the DE based approach) in p.u**
5	0.0387	0.0389	0.0391	0.0384	0.0388	0.0387
25	0.0553	0.0494	0.0265	0.0664	0.0649	0.0512
28	0.0650	0.0110	0.0179	0.0883	0.0115	0.0180
41	0.0581	0.0566	0.0520	0.0751	0.0662	0.0833
9	0.0884	0.0171	0.0416	0.1032	0.01	0.0667
18	0.0930	−0.0052	−0.1022	0.1365	−0.0227	0.0067
26	0.0735	0.0251	−0.0058	0.0860	0.0173	−0.0350
27	0.1430	0.0161	0.0391	0.1925	0.0070	0.0387

Table 4. Bus voltages & phase angles with and without FACTS devices for 200% reactive loading using GA & DE approach

Bus no.	**Bus voltage without FACTS**	**Bus voltages with FACTS using GA**	**Bus voltages with FACTS using DE**	**Bus angle (in radian) without FACTS**	**Bus angle (in radian) with FACTS using GA**	**Bus angle (in radian) with FACTS using DE**
7	1.0014	1.0082	1.0045	−0.1391	−0.1413	−0.1399
15	1.0036	1.0747	1.0646	−0.1795	−0.1746	−0.1764
17	1.0050	1.0797	1.0650	−0.1775	−0.1733	−0.1746
21	0.9956	1.0771	1.0566	−0.1816	−0.1800	−0.1794

Table 5. Amount of FACTS devices and other reactive sources in the transmission network with GA technique with different loading cases

Loading	**SVC amount (in p.u)**	**TCSC amount in lines (in p.u)**	**Reactive generation *Qg* (in p.u)**	**Transformer tap position (in p.u)**
100%	0.0892 0.0511 0.0398 0.0621	0.0001 0.0419 0.0002 0.0515	0.3409 0.1815 0.1911 0.1975 0.1023	0.9099 0.9859 0.9133 0.9344
150%	0.1586 0.1172 0.0714 0.1036	0.0010 0.0117 0.0002 0.0545	0.3899 0.1818 0.3185 0.2371 0.0971	0.9431 1.0109 0.9331 0.9081
175%	0.3351 0.2194 0.1877 0.1350	0.0008 0.0419 0.0008 0.0501	0.3630 0.2073 0.2158 0.1606 0.2500	0.9601 0.9004 0.9993 0.9482
200%	0.2399 0.1673 0.1149 0.1579	0.0011 0.0051 0.0004 0.0500	0.3318 0.2240 0.2751 0.2145 0.1357	0.9366 0.9880 0.9189 0.9001

Table 6. Amount of FACTS devices and other reactive sources in the transmission network with DE technique with different loading cases

Loading	**SVC amount in p.u**	**TCSC amount in lines in p.u**	**Reactive Generation *Qg in* p.u**	**Transformer tap position**
100%	0.1097 0.0427 0.0480 0.0958	0.0195 0.0419 0.0 0.0080	0.4287 0.0093 0.5 0.1995 0.0	0.9133 0.9 0.9 0.9283
150%	0.1279 0.1011 0.1025 0.2414	0.0 0.0 0.0405 0.0549	0.3280 0.0 0.0 0.4 0.3357	1.0236 0.9 0.94 0.9176
175%	0.2782 0.4706 0.2933 0.2766	0.0 0.0 0.0 0.0531	0.0609 0.6250 0.5 0.4 0.0	0.9631 0.9 1.1 0.9670
200%	0.2022 0.0811 0.1456 0.1498	0.0 0.0 0.0 0.0501	0.6 0.0 0.3893 0.0 0.2750	0.9666 1.0303 0.9220 0.9

Table 7. Comparative analysis of Operating Cost using GA & DE approach

Reactive Loading	**Operating cost due to the energy loss (in $) (A)**	**Operating Cost with FACTS devices using GA (in $) (B)**	**Operating Cost with FACTS devices using DE (in $) (C)**	**Cost of FACTS devices using GA (in $)**	**Cost of FACTS devices using DE (in $)**	**Net Saving using GA (in $) (A-B)**	**Net Saving using DE (in $) (A-C)**
100%	3737016	2.1786×10^6	2.1770×10^6	44664	43064	1558416	1560016
150%	3899952	2.3429×10^6	2.3470×10^6	67052	65896	1557052	1552952
175%	4020840	2.4745×10^6	2.4933×10^6	119812	86052	1546340	1527540
200%	4178520	3.1024×10^6	3.1118×10^6	90712	90544	1076120	1060520

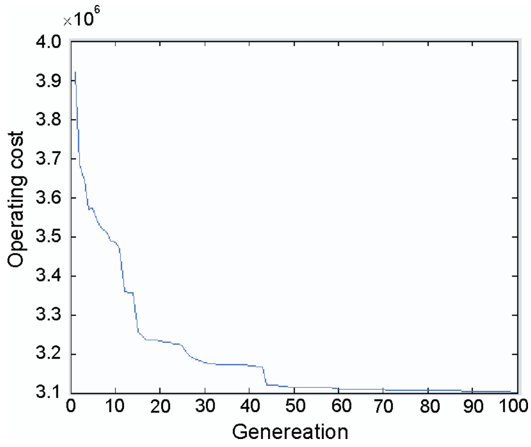

Fig. 4. Variations of operating cost with generation for reactive loading of 200% with GA

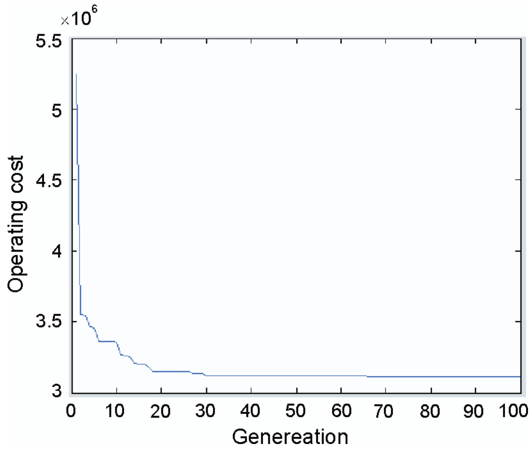

Fig. 5. Variations of operating cost with generation for reactive loading of 200% with DE

From Table 7 the net saving in the operating cost using DE is better than GA at 100% of base loading. At higher loading conditions, i.e. at 150%, 175% and 200% of base loading GA is more economical than DE. Reactive power flow in lines reduced significantly at different loading conditions using both GA & DE based approach which is observed from Table 3. Figures 4, 5 shows the variations of operating cost with generation for 200% of base reactive loading using GA & DE based technique respectively.
Here, energy cost is taken as 0.06 $/kWh.

6. Conclusions

In this research work the usefulness of DE (Differential Evolution) & GA based optimal placement of FACTS devices in a transmission network is tested for the increased load ability of the power system as well as to minimize the total operating cost since both GA & DE are two well known global optimization method. It has been observed that DE technique follows closely GA based approach in most of the loading cases. Still GA based algorithmic approach is found slightly advantageous over DE based approach in minimizing the overall system cost. The main objective of the work was to set power system parameters optimally so the overall operational cost reduces significantly even after installation of FACTS devices. Cost of FACTS devices are very less compared to the benefits in terms of the system operating cost for each cases of loadings in both DE & GA based approach. It is clearly evident from the results that effective placement of FACTS devices in proper locations by using suitable globally acceptable optimization technique like GA or DE can significantly improve system performance.

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