Evolutionary Programming for Reactive Power Planning Using FACTS Devices

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Abstract— This paper discusses the use of Genetic Algorithm (GA), Differential Evolution (DE) and Particle Swarm Optimization (PSO) based approach for the allocation & coordinated operation of multiple Flexible AC Transmission System (FACTS) devices for the economic operation as well as to increase power transfer capacity of an interconnected power system under different loading conditions. These Evolutionary programming based approaches for reactive power planning is applied on IEEE 30-bus system under different cases of loading. FACTS devices are installed in the different locations of the power system and system performance is noticed without and with FACTS devices. First, the locations, where the FACTS devices are to be placed are determined by calculating active and reactive power flows in the lines. GA, DE and PSO algorithms those under the category of Evolutionary Programming are used to find the magnitudes of the FACTS devices. Finally comparison between all these techniques for the placement of FACTS devices is presented.

Keywords- FACTS Devices, Line Power Flow, FACTS devices optimal locations, Active power loss, Operating cost, Evolutionary programming.

1 Introduction

In the present day scenario, due to increase in power demand, restriction on the construction of new lines, environment, unscheduled power flow in lines creates congestion in the transmission network and increases transmission loss. Effective control of reactive compensation on weak nodes improves voltage profile, reduces power loss and improves both steady state & dynamic performance of the system. With the development of FACTS devices, it has now become an obvious choice to use them in today's power system to extract maximum advantage out of it. The concept of flexible AC transmission system (FACTS) was first introduced by Hingorani. 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, both the active and reactive power flow in the lines can be controlled. Modeling and optimum location of variable FACTS devices are discussed in [1]-[2]. Power injection model of FACTS devices and Optimal Power Flow (OPF) model is discussed in [3] which present a novel power flow control approach to enable the working of different FACTS devices. The placement of different FACTS devices in a power system using Genetic Algorithm is discussed [4]. A GA based separate & simultaneous use of Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controller (UPFC), Thyristor Controlled Voltage regulator (TCVR), and Static Var Compensator (SVC) were studied in [5] for increased power flow. 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 [6] but the active power flow pattern can not be controlled. Power flow control with different FACTS devices were discussed in [7].
In this paper two types of FACTS devices have been discussed namely Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC). The main objective of this paper is to find the

optimal allocation of FACTS devices in the transmission network to minimize the transmission loss and also for the simultaneous increase of power transfer capacity of the transmission network that ultimately results minimum operating cost under different loading conditions.

2 FACTS Devices

2.1 Modelling 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's and SVC's are to control the power flow and voltages by adjusting the reactance of the system.

2.1.1 Thyristor Controlled Series Compensator (TCSC): In steady state, the TCSC can be considered as an additional reactance $-jX_{TCSC}$. TCSC acts as either inductive or capacitive compensator by modifying transmission line reactance. By installing TCSC's in transmission line power capacity increases and also the voltage profile improves. Transmission line admittance with TCSC is represented by

$$G_{TCSC}+jB_{TCSC} = \frac{1}{R + j(X_{Line} - X_{TCSC})} \quad (1)$$

where R and X_{Line} are the resistance and reactance of the line without TCSC and X_{TCSC} is the reactance with TCSC.

2.1.2 Static Var Compensator (SVC): The SVC can operate either in capacitive mode or in inductive mode. The function of SVC is either to inject reactive power to the bus or to absorb reactive power from the bus where it is connected. It improves the voltage in static and dynamic conditions and reduces active power loss.

2.2 FACTS Devices cost Functions

TCSC:

$C_{TCSC}=0.0015(OR)^2-0.7130(OR)+127.38(\$/kVar)$ (2)

SVC:

$C_{SVC}=0.0003(OR)^2-0.2691(OR)+188.22(\$/kVar)$ (3)

Here, (OR) is the operating range of the FACTS Devices.

3 Optimal Placement of FACTS devices

The installation of FACTS devices in a power system depends upon the following factors such as types of devices, location at which it is to be installed and its capacity. The decision where they are to be placed is largely dependent on the desired effect and the characteristics of the specific system. SVCs are mainly used to provide the voltage support at a particular bus and to inject reactive power flow in the adjacent lines. Power flow through the lines can also be changed by modifying the line reactance with the help of TCSC. For increasing the system ability to transmit power, FACTS devices are placed in such a way that it can utilize the existing generating units.

That is why FACTS devices are placed in the more heavily loaded lines to limit the power flow in those lines. This causes more power to be sent through the remaining portions of the system while protecting the line with the device for being overloaded. Reactive power flow in a line can be reduced by placing a TCSC in a line or by installing a SVC at the end of the line that also increases the active power flow capacity of the line simultaneously.

4 The Proposed Approach

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 and the cost of system operation, namely, energy loss costs are combined to form the objective function to be minimized. Besides FACTS devices, transmission loss can 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.

The optimal allocation of FACTS devices can be formulated as:

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

where $C_1(E)$ is the cost due to energy loss,

and $C_2(F)$ is the total investment cost of the FACTS devices.

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:

$$P_{Gi}-P_{Di}+P_i - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \quad (5)$$

$$Q_{Gi}-Q_{Di}+Q_{i(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \quad (6)$$

$$P_{Gj}-P_{Dj}+P_i - \sum_{j=1}^{N-1} V_j V_j (G_{jj}\cos\theta_{jj} + B_{jj}\sin\theta_{jj}) = 0 \quad (7)$$

$$Q_{Gj}-Q_{Dj}+Q_{j(inj)} - \sum_{j=1}^{N-1} V_j V_j (G_{jj}\sin\theta_{jj} - B_{jj}\cos\theta_{jj}) = 0 \quad (8)$$

SVC:

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

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 & 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 in all the cases of Genetic Algorithm and Differential Evolution and Particle Swarm Optimization based approaches.

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 25th, 41st, 28th & 5th found as the lines for TCSC placement and simultaneously series reactance of these lines are controlled.

4.1 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. These seventeen controlling parameters are represented with in a string. This is shown in Figure 1. 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 with every steps of GA and the second generation of same population size is produced. This procedure is repeated till the final goal is achieved.

4.2 Differential Evolution Technique in brief

Differential Evolution (DE) was developed by Storm & Price 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 1. 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.

4.3 PSO Approach in brief

The formulae on which PSO works is given as

$$V_i^{gen} = wV_i^{gen-1} + C_1 rand \times (p_{besti} - S_i^{gen-1}) + C_2 rand \times (g_{besti} - S_i^{gen-1})$$

$$S_i^{gen} = S_i^{gen-1} + V_i^{gen}$$

Where,

$V_i^{gen-1} \rightarrow$ current velocity of agent i at previous generation,

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{gen_{\max}} \times gen$$

$w \rightarrow$ weight function for velocity of agent i,

rand $\rightarrow$ is the random number between 0 and 1,

$S_i^{gen-1} \rightarrow$ current position of agent i at previous generation,

$C_i \rightarrow$ weight coefficient for each term,

$p_{besti} \rightarrow$ pbest of agent i,

$g_{besti} \rightarrow$ gbest of the group,

w is updated at each iteration,

Here $w_{\max}$ = 0.9, $w_{\min}$ = 0.4, $gen_{\max}$ = 500 and *gen* = current iteration, C_1 and C_2 are set to 2.0.

Also in PSO the control variables are represented with in a string as in figure 1. Initially strings are generated randomly and each string may be a potential solution. In PSO, each potential solution, called particles is assigned a velocity. The particles of the population always adjust their velocity depending upon their position with respect to the position of the *pbest* (the particle having the best fitness in the current generation) and the *gbest* (the particle having the best fitness upto the present generation). While adjusting their velocities and positions, particles adjust their fitness value as well. The particle having the best fitness among all is selected as the *pbest* for the current generation, and if this *pbest* has better fitness than the *gbest*, it takes the position of the *gbest* as well. In PSO, therefore, the *gbest* particle always improves its position and finds the optimum solution and the rest of the population follows it.

5 Test Results & Discussion

The proposed technique for the placement of FACTS devices is applied on IEEE 30 Bus system. The power system is loaded (reactive loading is considered) and FACTS devices are placed at different locations of the power system. The power system is loaded up to the limit of 200% of base reactive load and accordingly the system performance is observed with and without FACTS devices.

TCSC	SVC	Transformer Tap	Reactive Generations of Generators
4 Nos.	4 Nos.	4 Nos.	5 Nos.

Fig. 1 String representing the control variables

Figure 1 shows the different FACTS devices within a string. There are total 17 variables which are to be optimized using evolutionary techniques.

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 1 shows the locations of different FACTS devices in the transmission network. SVC's are connected at the buses 21st, 7th, 17th & 15th, the finishing ends of the lines 27th, 26th, 9th & 18th respectively, since these are the four lines carrying highest, second highest, third & fourth highest reactive power respectively. 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 27th, 26th, 9th & 18th in all cases of loading. TCSC's are placed in the lines 5th, 18th, 25th & 41st as these are the next four highest reactive powers.

Table 2. Bus Voltages & Phase Angles without and with FACTS devices for 200% Reactive loading using GA, DE and PSO

Bus No.	Bus Voltage without FACTS	Bus angle without FACTS	Evolutionary Methods with FACTS devices	Bus Voltage with FACTS	Bus angle with FACTS
7	1.0014	-0.1387	GA	1.0044	-0.1420
			DE	1.0045	-0.1399
			PSO	0.9952	-0.1383
15	1.0036	-0.1797	GA	1.0094	-0.1760
			DE	1.0646	-0.1764
			PSO	1.0574	-0.1711
17	1.0050	-0.1775	GA	1.0366	-0.1810
			DE	1.0650	-0.1746
			PSO	1.0662	-0.1696
21	0.9956	-0.1811	GA	1.0369	-0.1889
			DE	1.0566	-0.1794
			PSO	1.0684	-0.1773

The magnitude and phase angle of the voltages of weak nodes with & without FACTS devices for highest reactive loading i.e. for 200% is shown in Table 2. Phase angles are given in radian.

Table 3. Comparative analysis of Active Power Loss using Evolutionary methods

Reactive Loading	Active Power Loss without FACTS (p.u)	Active Power Loss with FACTS (p.u)		
		GA	DE	PSO
100%	0.0711	0.0406	0.0406	0.0445
150%	0.0742	0.0433	0.0434	0.0478
175%	0.0765	0.0448	0.0458	0.0497
200%	0.0795	0.0573	0.0576	0.0637

Table 3 shows the comparative analysis of active power loss using GA, DE & PSO based approach. It is clear that the active power loss is considerably less in GA and DE based method than the PSO based approach under different loading conditions.

Table 4 Comparative analysis of operating cost using Evolutionary methods

Reactive Loading	Operating Cost due to energy loss (in $) **(A)**	Evolutionary Methods with FACTS devices	Operating Cost $\times 10^6$ (in $) **(B)**	Net Saving (in $) **(A-B)**
100%	3737016	GA	2.1786	1558416
		DE	2.1770	1560016
		PSO	2.4052	1331816
150%	3899952	GA	2.3429	1557052
		DE	2.3470	1552952
		PSO	2.6080	1291952
175%	4020840	GA	2.4745	1546350
		DE	2.4933	1527540
		PSO	2.7693	1251540
200%	4178520	GA	3.1024	1076120
		DE	3.1118	1066720
		PSO	3.4460	732520

A comparative study of the operating cost of the system with and without FACTS devices using GA, DE & PSO is given in Table 4. From Table 4 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 based approach is slightly better than DE based method but found as more economical than PSO based technique.

Here, energy cost is taken as 0.06$/kWh.

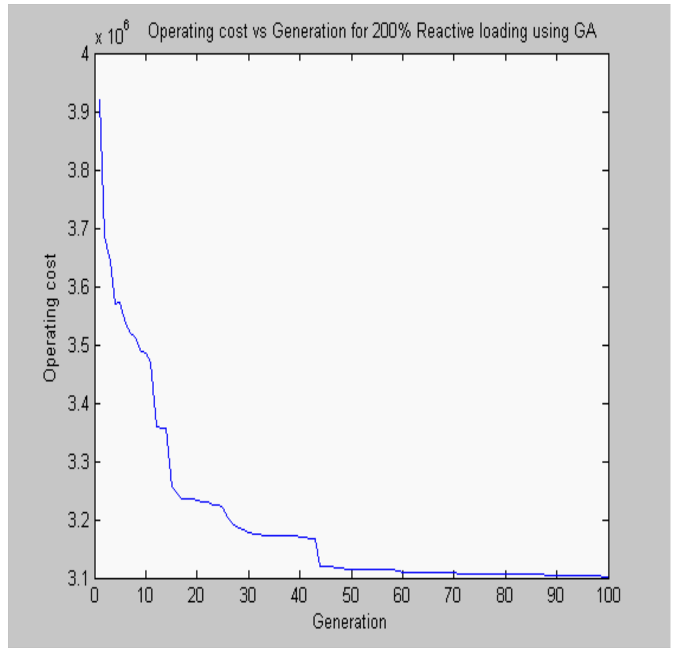

Fig. 2 Variation of operating cost with generation for reactive loading of 200% with GA

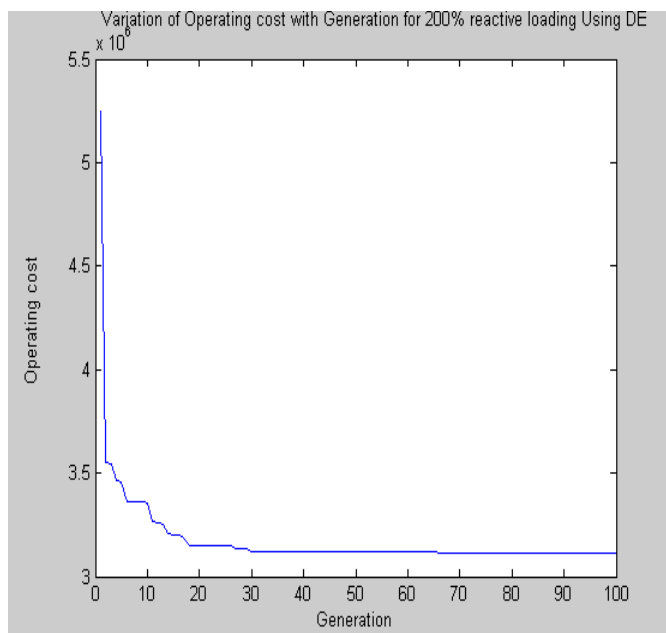

Fig. 3 Variation of operating cost with generation for 200% of base reactive loading using DE.

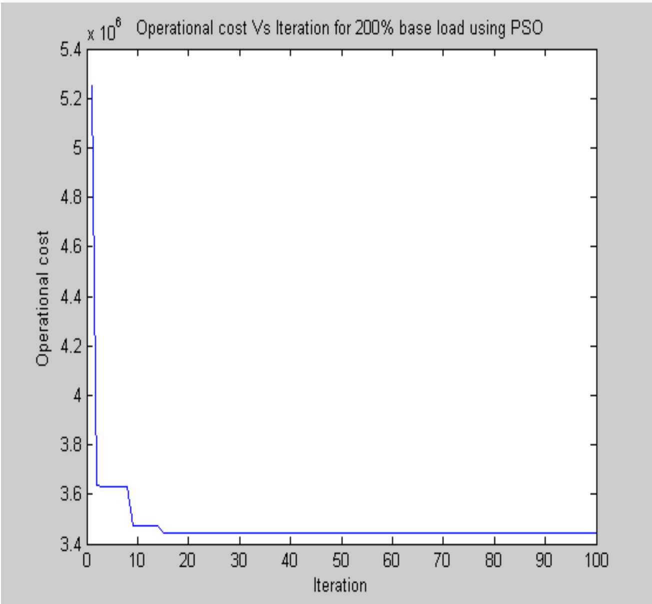

Fig. 4 Variation of operating cost with generation for 200% of base reactive loading using PSO.

Figures 2 to 4 shows the variation of operating cost with generation for base and 200% of reactive loading of the system with GA, DE and PSO based methods.

6 Conclusions

In this research work the usefulness of GA (Genetic Algorithm), DE (Differential Evolution) & PSO (Particle Swarm Optimization) 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. It has been observed that DE technique follows closely GA based approach in most of the loading cases and DE based algorithmic approach is found advantageous over PSO. Still GA based algorithmic approach is found slightly advantageous over DE based approach in minimizing the overall system cost. It is clearly evident from the results that effective placement of FACTS devices in proper locations by using proper optimization technique likes GA or DE can improve system performance significantly.

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