Application of DE & PSO Algorithm For The Placement of FACTS Devices For Economic Operation of a Power System

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Abstract— In this paper, use of Differential Evolution (DE) based and Particle swarm optimization (PSO) based algorithm for the allocation & coordinated operation of multiple FACTS (Flexible AC Transmission System) devices for the improved power transfer capacity and economic operation of an interconnected power system is presented. Both the DE and PSO based approach is applied on IEEE 30-bus system. The system is reactively loaded starting from base to 200 % of base load and the system performance is observed with and without FACTS devices. Active and reactive power flow in different lines gives an idea in determining the positions of FACTS devices to be placed in the system for the improved performance. Then the DE & PSO based optimization approach is applied to find the size of the FACTS devices and the comparative analysis between these two techniques are made. This differential evolution (DE) based approach for the installation of FACTS devices found as more beneficial than PSO based method.

Keywords - Line Power Flow, FACTS devices, Optimal location of FACTS devices, Operating cost, Differential Evolution, Particle Swarm Optimization.

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 represents the compensation degree of TCSC
X_C: Capacitive reactance of SVC reactor bank
X_L: Inductive reactance of SVC reactor bank
α: Firing angle of SVC
OR: 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, $Q_{i(inj)}$: 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

$Q_{iL(inj)}$: 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

In recent years power demand has increased substantially while the expansion of power generation and transmission has been limited due to limited resources and environmental restrictions. As a consequence some transmission lines are heavily loaded and system stability becomes a power transfer limiting factor. Flexible AC transmission system (FACTS) controllers are mainly used for solving various power system steady state control problems. However recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. 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. Tighter control of power flow 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]. 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 [16] for increased power flow.

The objective of this present work is the optimal allocation of FACTS devices in the transmission network so the transmission loss becomes minimized and also for the simultaneous increase of power transfer capacity of the transmission network that ultimately yields minimum operating cost under various loading conditions. 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 [17] but the active power flow pattern can not be controlled. A GA based approach is presented in [18] to determine the optimal location and rating of the FACTS devices in power system. Power flow control with different FACTS devices were 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.

2. FACTS devices

2.1 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_{Line} and $0.2X_{Line}$ is the maximum value of the inductance. When a TCSC is connected to a particular line, its admittance can be written as

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

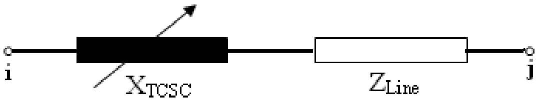

Fig 1. Mathematical Model of TCSC

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

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

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 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

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

The SVC model is shown in fig 2.

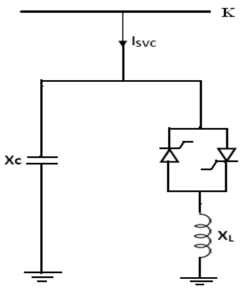

Fig. 2. SVC firing angle model

2.2 FACTS devices cost Functions

TCSC:

$$C_{TCSC}=0.0015(OR)^2-0.7130(OR)+127.38 \quad \text{(US\$/kVar)} \quad (3)$$

SVC:

$$C_{SVC}=0.0003(OR)^2 -0.2691(OR)+188.22 \quad \text{(US \$/kVar)} \quad (4)$$

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 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. 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

Here the main objective is to minimize the total operational cost under different loading conditions by installing FACTS devices at proper locations of the transmission network. Costs of the FACTS devices are to be taken into account while minimizing the operational system cost. 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. Minimization of transmission loss is nothing but a problem of reactive power optimization that can be done by controlling transformer tap setting positions, by controlling reactive generations of the generating units and by adding shunt capacitors at weak buses. But with the help of FACTS devices, active and reactive power flow pattern can be changed significantly and also the desired effects can easily be obtained. The optimal allocation of FACTS Devices can be formulated as:

$$C_{TOTAL} = C_1\,(E) + C_2\,(F) \quad (5)$$

Subject to the nodal active and reactive power balance

$$P_{ni}^{min} \leq P_{ni} \leq P_{ni}^{max}$$

$$Q_{ni}^{min} \leq Q_{ni} \leq Q_{ni}^{max}$$

voltage magnitude constraints: $V_i^{min} \leq V_i \leq V_i^{max}$

and the existing nodal reactive capacity constraints:

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}$$

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

TCSC:

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

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

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

$$Q_{Gj} - Q_{Dj} + Q_{j(inj)} - \sum_{j=1}^{N-1} V_j V_j (G_{jj}\sin\theta_{jj} - B_{jj}\cos\theta_{jj}) = 0 \quad (9)$$

SVC:

$$Q_{Gi} - Q_{Di} + Q_{iL(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \quad (10)$$

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 DE & PSO based algorithmic methods.

In this present work, first the locations of FACTS devices are obtained by calculating power flow in the lines. The TCSC positions are selected by choosing the lines carrying largest reactive power. Lines 25th, 41st, 28th & 5th are found as the lines for TCSC placement and simultaneously series reactance of these lines are controlled. SVC's are installed at 21st, 7th, 17th & 15th buses, where necessary reactive power injection and voltage support is required.

4.1 DE Technique in brief:

Differential Evolution (DE) developed by Storm & Price [20] is very similar to Genetic Algorithm (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 is shown in fig 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.

4.2 PSO Approach in brief:

The basic approach for the optimization of nonlinear functions using particle swarm optimization technique is introduced in [21].
The formulae on which PSO works is given as

$$\upsilon_i^{k+1} = \omega_i \upsilon_i^k + C_1 \text{ rand } \times \left(P_{best_i} - S_i^k\right) + C_2 \text{ rand } \times \left(g_{best} - S_i^k\right)$$

Where,

$\upsilon_i^k \rightarrow$ current velocity of agent *i* at iteration *k*,

$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \rightarrow$ is the modified velocity of the ith agent

rand →is the random number between 0 and 1,

$S_i^k \rightarrow$ current position of agent *i* at iteration *k*,

$C_i \rightarrow$ weight coefficient for each term,

$P_{best_i} \rightarrow P_{best}$ of agent *i*,

$g_{best} \rightarrow g_{best}$ of the group,

$\omega_i \rightarrow$ weight function for velocity of agent *i*.

Where ω is updated by the following equation at each iteration

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter$$

Here $\omega_{\max}$ =0.9, $\omega_{\min}$ = 0.4, $iter_{\max}$ = 500 and $iter$ = 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 fig 3. 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.

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 DE & PSO approach

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

Table 3 Comparative analysis of operating cost using DE approach

Reactive Loading	Operat-ing cost due to the energy loss (in \$) (A)	Operating Cost with FACTS devices using DE (in \$) $\times 10^6$ (B)	Cost of FACTS devices Using DE (in \$)	Net Saving Using DE (in \$) (A-B)
100%	3737016	2.1770	43064	1560016
150%	3899952	2.3470	65896	1552952
175%	4020840	2.4933	86052	1527540
200%	4178520	3.1118	90544	1060520

Table 4 Comparative analysis of operating cost using PSO approach

Reactive Loading	Operat-ing cost due to the energy loss (in \$) (A)	Operating Cost with FACTS devices using PSO (in \$) $\times 10^6$ (C)	Cost of FACTS devices Using PSO (in \$)	Net Saving Using PSO (in \$) (A-C)
100%	3737016	2.4052	66280	1331816
150%	3899952	2.6080	95632	1291952
175%	4020840	2.7693	157068	1251540
200%	4178520	3.4460	97900	732520

Table 5 Comparative study of reactive power flow in line with DE

Lines	For base reactive loading of 150% (before) 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 DE based approach) In p.u
5	0.0387	0.0391	0.0384	0.0387
25	0.0553	0.0265	0.0664	0.0512
28	0.0650	0.0179	0.0883	0.0180
41	0.0581	0.0520	0.0751	0.0833
9	0.0884	0.0416	0.1032	0.0667
18	0.0930	-0.1022	0.1365	0.0067
26	0.0735	-0.0058	0.0860	-0.0350
27	0.1430	0.0346	0.1925	0.0295

Table 6 Comparative study of reactive power flow in line with PSO

Lines	For base reactive loading of 150% (before) In p.u	For base reactive loading of 150% (By the PSO based approach) In p.u	For base reactive loading of 200% (before) In p.u	For base reactive loading of 200% (By the PSO based approach) In p.u
5	0.0387	0.0383	0.0384	0.0380
25	0.0553	0.0611	0.0664	0.0879
28	0.0650	0.0388	0.0883	0.0495
41	0.0581	0.0207	0.0751	0.0388
9	0.0884	0.0525	0.1032	0.0714
18	0.0930	-0.0627	0.1365	-0.0034
26	0.0735	0.1259	0.0860	0.1544
27	0.1430	0.0778	0.1925	0.0923

Here, energy cost is taken as 0.06$/kWh for the calculation operating cost due to energy loss

5. Test Results & Discussion

The proposed approach for the placement of FACTS devices is applied on IEEE 30 Bus system. The power system is loaded (reactive loading is considered) and accordingly 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 the 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 DE & PSO approach. A comparative study of the operating cost of the system with FACTS devices using DE & PSO technique is shown in Table 3 & Table 4. The change in reactive flow pattern in the lines where FACTS devices are connected for 150% and 200% base reactive loading is shown in Table 5 & Table 6 by using DE & PSO technique. From Table 1 it is observed that SVC's are connected at the buses 21st, 7th, 17th & 15th those are at the finishing ends of the lines 27th, 26th, 9th & 18th respectively because these are the four lines carrying highest, second highest, third and fourth highest reactive power respectively. After connecting SVC's at theses buses reactive power flow reduces greatly in the lines 27th, 26th, 9th & 18th in each case of loading. TCSC's are placed in the lines 25th, 41st, 28th & 5th.

From Table 2, 3 & 4 we observe that transmission loss as well as operational cost reduced significantly in all cases of loading with FACTS devices as compared to without such devices. Significant economic gain is obtained even at a loading of 200% of base reactive loading which is also evident from Table 3 & Table 4. The economic gain obtained is much higher than the installation cost of FACTS devices in every cases of loading. From table 2 it is clear that the active power loss in DE based approach is considerably less compared to PSO based technique in all cases of loading. Also the overall saving using the DE based approach is found as much better than PSO based technique that is observed from table 3 & 4 i.e. DE is found as more economical approach than PSO based approach. Reactive power flow in lines reduced significantly at different loading conditions in both the DE and PSO based techniques as observed from table 5 & 6 respectively.

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Fig 4 and fig 5 shows the variation of operating cost with generation for 200% of base reactive loading using DE & PSO based technique respectively.

TCSC				SVC				Transformer Tap				Reactive Generations of Generators				
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	5

Fig. 3. String representing the control variables

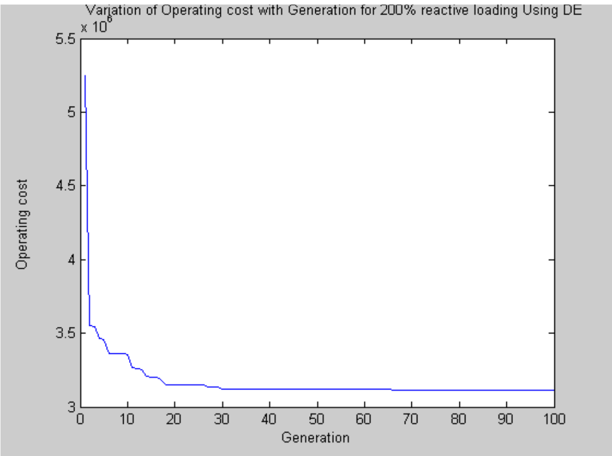

Fig. 4. Variation of operating cost with Generation for 200% of base reactive loading using DE.

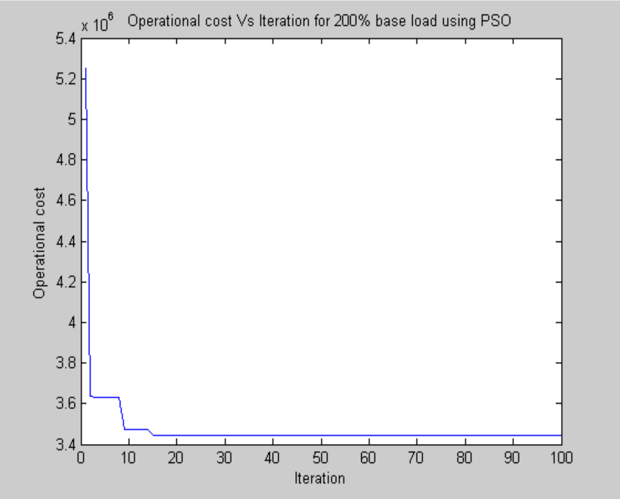

Fig. 5. Variation of operating cost with Generation for 200% of base reactive loading using DE.

6. Conclusions

In this approach, DE (Differential Evolution) & PSO (Particle Swarm Optimization) based optimal placement of FACTS devices in a transmission network is presented for the increased load ability of the power system as well as to minimize the total operating cost. DE based algorithmic approach is found advantageous over PSO based approach in minimizing the overall system cost. Cost of FACTS devices are very less compared to the benefits in terms of the system operating cost for each cases of loadings that are clearly observed. Two different types of FACTS devices are considered. It is clearly evident from the results that effective placement of FACTS devices using suitable optimization technique can significantly improve system performance. After comparative analysis between the DE & PSO based approach, DE based method is found as more advantageous from the economic point of view and can be used as a suitable optimization method for the proper placement of FACTS devices in the transmission network.

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