Optimal Placement and Sizing of Multi-type Facts Devices Using PSO and HSA

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Abstract. Voltage stability is an important issue in power system operation. Flexible AC transmission systems, so-called FACTS devices, help to improve voltage stability and minimize real power losses. The effectiveness of FACTS devices depend on their proper location and rating. This paper presents a method, based on line flow sensitivity factors such as bus voltage stability index and line voltage stability index, to find suitable locations of multi-type FACTS devices. Also this paper proposes an application of particle swarm optimization (PSO) and harmony search algorithm (HSA) in optimizing the rating of FACTS devices. The proposed approaches are evaluated with three different objective functions namely, minimization of real power loss, improvement of voltage profile and enhancement of voltage stability. The performance of proposed methods is analyzed on IEEE 14 bus system by implementing FACTS devices such as static var compensator (SVC), thyristor controlled series capacitor (TCSC) and unified power flow controller (UPFC).The analysis shows that there is a reduction in real power loss and improvement in voltage stability and voltage profile of the system after employing FACTS devices. It also shows that both real power loss and bus voltage stability index (BVSI) have been reduced more with FACTS ratings obtained from PSO than with that from HSA.

Keywords: Voltage stability · SVC · TCSC · UPFC · PSO · HSA

1 Introduction

Modern power system is a complex nonlinear interconnected network. It consists of interconnected transmission lines, generating plants, transformers and a variety of loads. With the increase in power demand, it is more essential to improve the voltage profile of the system. Also voltage stability is a problem in power systems which are overloaded, faulted or have a shortage of reactive power. When a bulk power transmission network operates near to its voltage stability limit, it becomes complicated to control its reactive power demand. Thus enhancement of voltage stability is a major concern in power system.

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Voltage stability is defined as *the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance*. Voltage instability occurs mainly due to the happening of sag in reactive power at various locations in an interconnected power system. Instability results as a form of a progressive fall or rise of voltages at some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages [1].

During the last decade, a number of control devices under the term FACTS technology have been proposed and implemented. Application of FACTS devices in modern power systems leads to better performance of the system. FACTS devices enhances system parameters like voltage stability, voltage regulation, power system loadability and enhancement of damping. There are various forms of FACTS devices, some are connected in series with line and the others are connected in shunt or a combination of series and shunt [2]. The FACTS technology is not a single high power controller but rather a group of controllers which can be applied individually or in coordination with other to control one or more of the inter related system parameters like impedance, voltage, current, and phase angle.

In this paper, multi type of FACTS devices such as static VAR compensator (SVC), thyristor controlled series capacitor (TCSC) and unified power flow controller (UPFC) are discussed. The performance of power system can be enhanced to a greater extent with these devices, only when they are located at proper location with optimal rating. Several methods have been adopted to determine optimal location and rating of FACTS devices.

In earlier days, some authors have used analytical methods like linear programming (LP) [3] and mixed integer linear programming (MILP) [4] to optimize the location of FACTS devices in order to obtain system need. Now-a-days, different AI techniques such as genetic algorithm (GA) [5–7], tabu search (TS), simulated annealing (SA), hybrid TS/SA [8], hybrid TS/PSO [9] and particle swarm optimization (PSO) [10] are used to find optimal location and sizing of FACTS devices. In paper [11–13] various parameters like real power flow performance index, Line flow sensitivity index and locational marginal price (LMP) were taken as the criteria to determine optimal location of multiple FACTS devices.

This paper, proposes a method for finding the optimal location and rating of multi type FACTS devices using sensitivity analysis and optimization algorithm in order to minimize the real power loss, to improve voltage profile and to enhance voltage stability. The voltage stability of the system is analyzed using voltage stability index approach. Based on the sensitivity indices, weak load bus and weak transmission line which needs significant reactive power support are identified. To find the optimal sizing optimization algorithms like harmony search algorithm (HSA) and particle swarm optimization (PSO) are used. Both PSO and HSA are known to effectively solve large scale nonlinear optimization problems. Harmony search algorithm works based on action of orchestra music to find the best harmony among various instruments whereas PSO algorithm resembles the flocking behavior of birds. The proposed approaches have been tested on IEEE 14-bus system and the results are presented. The test results show that the sizing of the FACTS devices identified by PSO gives better enhancement of voltage stability and minimization of losses than that of HSA.

2 Stability Indices

In power system, the stability level of all load buses and all lines can be identified with the help of the stability indices. In this paper bus voltage stability index (BVSI) and line voltage stability index (LVSI) are used to find the weakest load bus and transmission line respectively.

Line Voltage Stability Index (LVSI): LVSI represents the stability index for each line connected between two buses in an interconnected transmission system. Based on these indices, voltage stability levels can be predicted. When the stability index L_{mn} less than 1, the system is stable and when this index exceeds the value 1, the corresponding line loses its stability and voltage collapse occurs. LVSI can be calculated as,

$$L_{mn} = \frac{4X_n Q_n}{(V_m \sin(\theta_{mn} - \delta_m))^2} \tag{1}$$

where,

V_m - sending end voltage
Q_n - reactive power at receiving end
X_n - Reactance at receiving end
θ_{mn} - Impedance angle
δ_m - Angle difference between the supply voltage and the receiving end voltage

Bus Voltage Stability Index (BVSI): For a given load condition BVSIs are determined for all load buses. If this index value is moving towards zero, then the system is considered as stable and also improves system security. When this index value moves away from zero, the stability of system relatively decreases and the system is considered as unstable. The voltage stability index for load buses is to be computed as

$$L_j = \left| 1 - \sum\nolimits_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \tag{2}$$

where,

j = g+1….N, total number of buses
g- No of generators connected in the system.
V_i – voltage of the ith generator bus
V_j – voltage of the bus j for which L_j has to be calculated

The values of F_{ji} can be obtained from Y bus matrix.

$$F_{ji} = [Y_{LL}]^{-1}[Y_{LG}] \tag{3}$$

where, Y_{LL} and Y_{LG} are corresponding partitioned portions of the Y-bus matrix.

3 Problem Formulation

The objective function of this paper is to find the optimal rating of FACTS devices which minimizes real power loss, improves voltage profile and enhances voltage stability is given by,

$$minf = \sum\nolimits_{l=1}^{n} P_L^l + \sum\nolimits_{i=1}^{n-g} V_{D_i} + \sum\nolimits_{j=1}^{n-g} L_j \tag{4}$$

where

P_L^l - Real power in a line l

V_{D_i} - Voltage deviation of load bus i, which is given by, $V_{D_i} = (1 - V_i)^2$ (5)

V_i - Voltage at bus i

L_j - Bus Voltage Stability Index (BVSI) of load bus j

3.1 Real Power and Bus Voltage Constraints

$$J = \prod\nolimits_{LINE} OVL_{LINE} * \prod\nolimits_{BUS} VS_{BUS} \tag{6}$$

J is the factor indicating violation of line flow limits and bus voltage limits, where OVL denotes line overload factor for a line and VS denotes voltage stability index for a bus.

$$OVL = \begin{cases} 1; & if\, P_{pq} \leq P_{pq}^{max} \\ e^{(\mu\left|1-\frac{P_{pq}}{P_{pq}^{max}}\right|}; & if\, P_{pq} > P_{pq}^{max} \end{cases} \tag{7}$$

$$VS = \begin{cases} 1; & if\, 0.9 \leq V_b \leq 1.1 \\ e^{(\lambda|1-V_b|}; & Otherwise \end{cases} \tag{8}$$

where,

P_{pq} - Real power flow between buses p and q

P_{pq}^{max} - Thermal limit for the line between buses p and q

V_b - Voltage at bus b

λ and μ - Positive constants both equal to 0.1

3.2 FACTS Device's Constraints

$$-0.8X_L \leq X_{TCSC} \leq 0.2X_L p.u \tag{9}$$

$$-0.9 \leq B_{SVC} \leq 0.9 p.u \tag{10}$$

(9) and (10) for UPFC

where,

X_{TCSC} - Reactance added to the line by TCSC
X_L - Reactance of the line where TCSC is located
B_{SVC} - Susceptance added to the bus by SVC

4 Harmony Search Algorithm

Harmony search algorithm is a meta-heuristic optimization algorithm which works based on the act of orchestra music to find the best harmony among various components which are involved in the process to find optimal solution. In orchestra music, musical instruments can be played with some distinct musical notes based on player's experience or based on random improvisation processes. Similar to that optimal design variables for HSA are to be obtained with certain distinct values based on some computational intelligence and random processes. HSA can consider both discontinuous functions and continuous functions because it doesn't need differential gradients and initial value setting for the variables and it is also free from divergence and can escape from local optima. HS algorithm will always looks for vector that can reduce the cost function or objective function. The major steps involved in the HS algorithm are described as follows [14, 15]:

(1) Initialization of objective function
(2) Initialization of the harmony memory
(3) Improvisation a new harmony from the HM set
(4) Updating harmony memory
(5) Checking stopping criterion.

The parameters used in harmony search algorithm are given in Table 1.

Table 1. HSA parameters

Parameter	Value
Harmony memory size (HMS)	100
Number of improvisation (NI)	2000
Harmony memory considering rate (HMCR)	0.95
Maximum pitch adjustment rate (PAR max)	0.9
Minimum pitch adjustment rate (PAR min)	0.2
Bandwidth (bw)	0.2

4.1 Pseudo Code for Harmony Search Algorithm

```
Specify the algorithm parameters (HMS, NI, HMCR, $PAR_{max}$, $PAR_{min}$, bw, $L_i$, $U_i$
Initialize the harmony memory $x_i$randomly
Set iter=1
for k=1: HMS
        Run Newton Raphson power flow by connecting FACTS devices in optimal location and evaluate the
    fitness value using equation (4) $f_i$ from load flow results.
end
for iter =1: NI
    for t =1: HMS
        if probability < HMCR
                $x_i^t \epsilon \{x_1^t, x_2^t, x_3^t \dots\dots x_{HMS}^t\}$
            $PAR(iter) = PAR_{min} + \frac{PAR_{max} - PAR_{min}}{NI} \times iter$
            if probability<PAR(iter)
                $x_i^t = x_i^t \pm bw$
            end
        else
                $x_i^t \in [L_i, U_i]$
        end
        With new harmony $x_i$calculate the fitness value $f_i^t$
    $if f_i^t < f_i$
            $f_i$=$f_i^t$; $x_i$=$x_i^t$
        end
    end
end
```

5 Particle Swarm Optimization

Particle swarm optimization (PSO) is a kind of optimization algorithm used to obtain the optimal solution by simulating the schooling behavior of fishes or flocking behavior of birds. Initially a flock of birds, in which each bird called as a particle is made to fly over the searching space. These particles will fly with certain velocity to find the best global position (G_{best}) after some iteration. For each and every iteration, current position and velocity of all particle gets changed according to its current position P_{best} and the current global position G_{best}. Thus all the particles will move towards the global solution at the end of maximum iteration [16].

Velocity of each particle can be modified by the following equation

$$V_i^{k+1} = w \times v + c_1 \times rand_1 \times \left(P_{best_i} - s_i^k\right) + c_2 \times rand_2 \times \left(G_{best_i} - s_i^k\right) \tag{11}$$

where,

V_i^{k+1} - Velocity of ithparticle at iteration k + 1

w - Weight function, which is given by, $w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} iter$

w_{max} - Initial inertia weight

w_{min} - Final inertia weight

$iter_{max}$ - Maximum iteration number (12)

$iter$ - Current iteration number

c_1, c_2 - Weight coefficient

$rand_1, rand_2$ - Random number between 0 and 5

P_{best_i} - Best position of particle i upto current iteration

G_{best_i} - Best overall position found by the particle upto current iteration

Now the new position can be obtained using,

$$s_i^{k+1} = s_i^k + V_i^{k+1} \tag{13}$$

5.1 PSO Algorithm to Find Optimal Rating of FACTS Devices

Step 1 : Read bus data, line data and FACTS devices (SVC, TCSC and UPFC) data
Step 2 : Specify PSO parameters and maximum number of iterations
Step 3 : The initial population of particles are generated with random position and velocity
Step 4 : Run Newton Raphson power flow by connecting FACTS devices in optimal location
Step 5 : Evaluate the fitness value using Eq. (4) for each particle from load flow results
Step 6 : Save the minimum value of fitness as P_{best} and its corresponding particles as G_{best}
Step 7 : Set iteration count equal to 1
Step 8 : Particle positions and velocities are updated using (11) and (13) respectively
Step 9 : Again for each particle the fitness function is calculated and if it is higher than the individual P_{best} then it is the current P_{best} and store the current position
Step 10 : The particle with the minimum P_{best} value among all particles is chosen as the overall G_{best} value
Step 11 : If the maximum number of iteration is reached, then the position of global best particles corresponding to optimal solution will be the optimal location of FACTS device. Otherwise increase the iteration count and go to step 9

The parameters of PSO used in this paper are given in Table 2.

Table 2. PSO parameters

Parameter	Value
No. of particles	30
No. of iterations	250
C1	1
C2	3
Initial inertia weight	0.9
Final inertia weight	0.8

6 Results and Discussions

The performances of proposed methods were analyzed by employing various combinations of FACTS devices in IEEE- 14 bus system using MATLAB and their results were presented.

6.1 Base Case Results

The IEEE-14 bus system was used as a test system. The IEEE 14 bus system consists of 5 generator buses, 9 load buses and 20 transmission lines. The load flow is performed on the test system using Newton Raphson load flow analysis since it is faster, reliable, gives more accurate results, requires less number of iterations and does not depend on size of system [17]. From the load flow results, LVSI and BVSI were determined for all lines and load buses using Eqs. (3) and (4) respectively to find the stability level of system.

6.2 Determination of Optimal Location of FACTS Devices Using Stability Indices

The transmission lines and load buses were ranked according to LVSI and BVSI. The lines and load buses that occupy the top ranks were taken as optimal location of FACTS devices. The candidate locations of SVC are found based on BVSI and those for TCSC and UPFC are found based on LVSI. It can be observed from Table 1 that for IEEE-14 bus system, the lines 5–6, 4–7, 7–8, 4–9 and 1–2 having the highest value of LVSI, are taken as the most suitable locations for TCSC and UPFC. Thus the five optimal locations of SVC, TCSC and UPFC for IEEE-14 bus are given in Table 3.

Table 3. Five possible locations of TCSC and UPFC

Rank	IEEE-14 bus system			
	Branch no	From bus	To bus	LVSI
1	10	5	6	0.2658
2	8	4	7	0.1458
3	14	7	8	0.1430
4	9	4	9	0.0880
5	1	1	2	0.0715

6.3 Determination of Optimal Sizing of FACTS Devices Using HSA and PSO

After finding optimal location of various FACTS devices, optimal capacity of FACTS devices have been obtained using HSA and PSO which is explained in Sects. 4 and 5, by placing various combinations of SVC, TCSC and UPFC at their suitable locations in IEEE-14 bus system. The optimal capacities of FACTS devices obtained from HSA and PSO and their effects on system parameters like total real power loss and total bus voltage stability index (BVSI) are given for IEEE-14 bus in Table 4. Let the first

Table 4. Optimal capacity of multi type FACTS devices and their effects in IEEE-14 bus system

No of FACTS devices	Type of FACTS device	Count	HSA				PSO			
			Location	Rating (p.u)	Active power loss reduction (MW)	Total BVSI reduction	Location	Rating (p.u)	Active power loss reduction (MW)	Total BVSI reduction
3	TCSC	1	Branch-10	−0.0197	7.4286	1.4523	Branch-10	−0.2255	7.8849	1.7736
	SVC	1	Bus-12	−0.5871			Bus-12	−0.5459		
	UPFC	1	Branch-10	−0.7576			Branch-10	−0.6980		
				−0.8349				−0.8978		
4	TCSC	2	Branch-10	−0.3019	7.0988	1.0893	Branch-10	−0.0121	7.8292	1.4445
			Branch-8	−0.3126			Branch-8	−0.4806		
	SVC	1	Bus-12	−0.4870			Bus-12	−0.5493		
	UPFC	1	Branch-10	−0.7144			Branch-10	−0.3900		
				−0.7787				−0.8986		
4	TCSC	1	Branch-10	−0.0146	9.7462	1.4243	Branch-10	−0.1555	10.0585	1.7965
	SVC	1	Bus-12	−0.0916			Bus-12	0.0590		
	UPFC	2	Branch-10	−0.2066			Branch-10	−0.6985		
				−0.7148				−0.7942		
			Branch-8	−0.2438			Branch-8	−0.6403		
				−0.7449				−0.8984		
4	SVC	2	Bus-12	−0.5863	9.7363	1.4951	Bus-12	−0.3007	9.8813	1.594
			Bus-13	0.5761			Bus-13	0.0856		
	UPFC	2	Branch-10	−0.6188			Branch-10	−0.5268		
				−0.8436				−0.4907		
			Branch-8	−0.7027			Branch-8	−0.5101		
				−0.8817				−0.8954		
4	TCSC	2	Branch-10	−0.7206	6.8713	1.4482	Branch-10	−0.7984	7.0317	1.4746
			Branch-8	−0.0799			Branch-8	−0.3025		
	SVC	2	Bus-12	−0.7372			Bus-12	−0.8700		
			Bus-13	−0.5821			Bus-13	−0.5070		

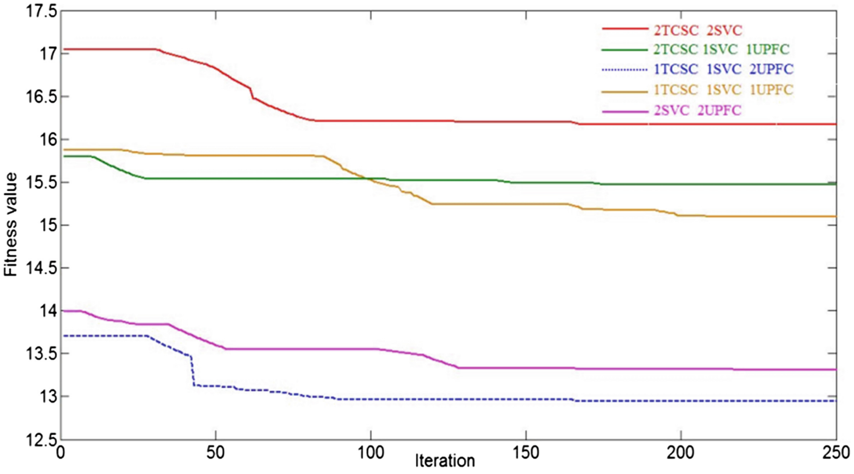

Fig. 1. Fitness curves for multi-type FACTS devices in IEEE-14 bus system

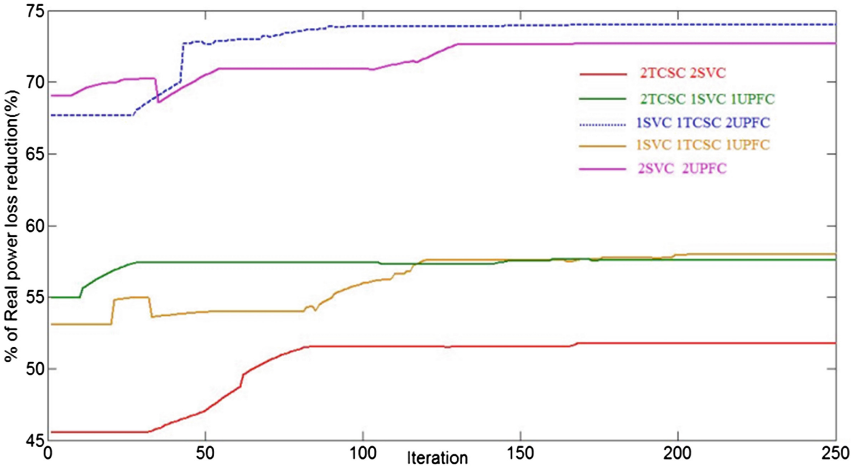

Fig. 2. Loss reduction curves for multi-type FACTS devices in IEEE-14 bus system

combination of FACTS devices be 1TCSC, 1SVC and 1UPFC. While finding the optimal rating of these devices using HSA, real power loss reduction percentage is obtained as 54.65 % and that of BVSI is 14.21 %, whereas in PSO both loss and BVSI gets reduced even more i.e. loss reduction percentage is 58 % and for BVSI it is 17.36 %.

The effects of various combinations of FACTS devices on fitness value and real power loss in IEEE-14 bus system are observed from PSO algorithm and are shown in Figs. 1 and 2 respectively. From Figs. 1 and 2 it can be observed that, in IEEE-14 bus system, by having a combination of 1TCSC, 1SVC and 2UPFC, minimum fitness value

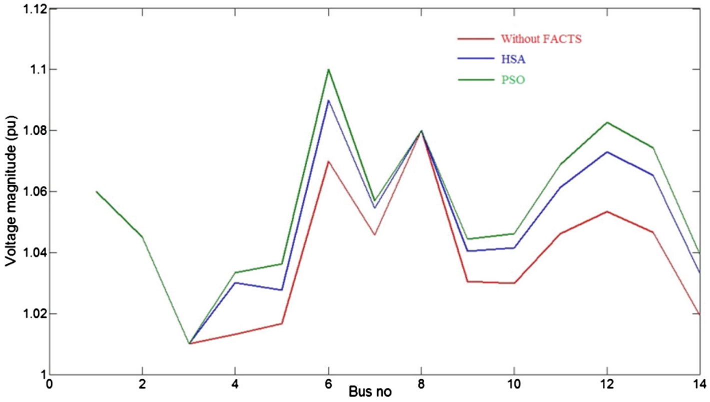

Fig. 3. Voltage profile improvement curve for IEEE-14 bus system with 1TCSC, 1SVC and 2UPFC

of 12.9466 and maximum loss reduction percentage of 73.99 is achieved whereas, minimum loss reduction of 51.73 % is obtained using 2TCSC and 2SVC combination.

The Fig. 3 shows the voltage profile of IEEE-14 bus system with and without FACTS devices. From the figure, it can be observed that voltage profile have been improved with FACTS ratings obtained from PSO than with that from HSA.

7 Conclusion

In this paper, a sensitivity based method related to stability level of the power system and optimization algorithms like harmony search algorithm (HSA) and particle swarm optimization (PSO) has been proposed to determine optimal location and sizing of multi-type FACTS devices. The proposed approach is efficient and simple since it uses sensitivity factors, which can be easily updated for future expansion. Different FACTS devices implemented are SVC, TCSC and UPFC. The suitable location for different combination of FACTS devices are obtained by calculating bus voltage stability index (BVSI) and line voltage stability index (LVSI). The optimal capacity of FACTS devices for minimizing real power loss, improving voltage profile and enhancing voltage stability are found using HSA and PSO algorithm. Simulations are done using MATLAB software and the results are presented for test system namely IEEE-14. The analysis shows that there is a reduction in real power loss and improvement in voltage stability and voltage profile of the system after employing FACTS devices. It also shows that both real power loss and total BVSI have been reduced more with FACTS ratings obtained from PSO than with that from HSA.

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