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Improving Voltage Stability of Power System by Optimal Location of FACTS Devices Using Bio-Inspired Algorithms

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Abstract

Power system operations can be optimized using power electronics based FACTS devices. The location of these devices at appropriate transmission line plays a major role in their performance. In this paper, two bio-inspired algorithms are used to optimally locate two FACTS devices: UPFC and STATCOM, so as to reduce the voltage collapse and real power losses. Particle swarm optimization and BAT algorithms are chosen as their behaviour is similar. VCPI index is used as a metric to calculate the voltage collapse scenario of the power system. The algorithm is tested on two benchmark power systems: IEEE 118 and the Indian UPSEB 75 bus system. Performance metrics are compared with the system without FACTS devices. Application of PSO and BAT algorithms to optimally locate the FACTS devices reduces the VCPI index and real power losses in the system.

Keywords

BAT, FACTS, Optimal Location, PSO, STATCOM, UPFC, Voltage Stability

1. Introduction

With current trends in decreasing fossil fuels, increasing pollution levels, and uncontrolled increase in population, power system optimization is the need of the hour. Various parameters in the power system like voltage, frequency, active and reactive power, harmonic distortion and power factor requires control. Power electronic devices play a major role in optimizing these parameters. With the advent of Flexible AC Transmission (FACTS) Devices, it has become possible to control multiple power system parameters using single device. Thyristor Controlled Series Compensator (TCSC), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC) are few devices that are installed in the power system

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network to enhance controllability and power transfer capability. Each of these FACTS devices provide different benefits to the power system and hence using more than one FACTS device can optimize different parameters, making the power system more reliable. Since real time power systems are huge complex networks with many transmission lines, it is important to find a suitable location for these devices. Placing a FACTS device randomly in a location will not satisfy the objective, and sometimes will produce negative effect on the network.

Many algorithms are used to locate these FACTS devices optimally in the system with different objectives. Genetic algorithm (GA) is widely used to locate FACTS devices. In [1], GA is applied to find optimal location of four FACTS devices namely UPFC, TCSC, TCPST and SVC, with cost as the objective function. Firefly algorithm is used in [2] to locate SVC with power loss and voltage deviation control. Particle Swarm Optimization (PSO) based method [3]-[6] is applied to this problem with different types of objectives in the literature. In [7]-[9], artificial bee colony algorithm is used to locate FACTS devices. To minimize average loadability to relieve overloads, a linear programming [10] and a non-linear programming [11] based optimal location of UPFCs are presented in the literature. A fuzzy [12] approach based optimal location of UPFC under network contingencies is simulated to improve system stability and security. In this paper two types of FACTS devices: UPFC and STATCOM are used as UPFC is one of the best FACTS device, operating under system insecurity [13] [14]. STATCOM is also capable of operating under various stressed conditions of the power system [15] [16]. PSO and BAT algorithms are used to find the optimal location of these devices with multi-objective optimization. Voltage stability and real power loss are considered as optimizing parameters, with voltage deviation penalty. The proposed algorithm is tested on the standard IEEE 118 bus system and the UPSEB 75 bus system with different loading conditions.

2. Problem Formulation

Power injection model is used for both STATCOM and UPFC. STATCOM is modeled as a controllable voltage source (Estat ∠θstat) in series with an impedance (Ystat) (**Figure 1**).

Power injection model (**Figure 2**) is used in this paper, in which UPFC is represented as two voltage sources in steady state between buses *i* and *j*.

Voltage stability is a major concern in power system, especially during load variations. An accurate and reliable index was proposed by Moghavvemi and Faruque [17] to analyse the stability of the system. Voltage stability proximity indicator is based on the maximum power that is transferred between two nodes in a power system network. It is expressed as in Equation (1) [17].

$$VCPI = \frac{P}{P_{\max}} = \frac{Q}{Q_{\max}} \tag{1}$$

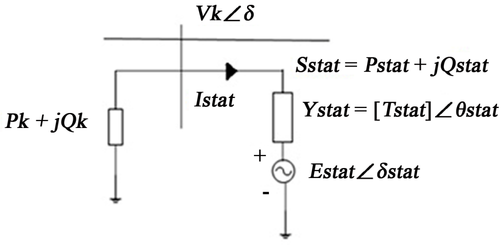

Figure 1. STATCOM steady state model.

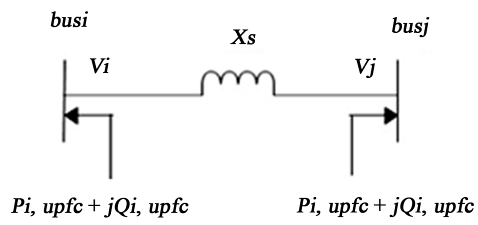

Figure 2. UPFC power injection model.

where P, Q are the real and reactive power transferred and P_{max} and Q_{max} are the maximum values of real and reactive power that can be transferred over a line. The objective of this paper is to reduce the value of VCPI of the power system by using FACTS devices. FACTS devices like STATCOM and UPFC are generally installed in power systems to improve voltage stability. In a large power system network, these FACTS devices can be placed in many possible nodes, and at each location the performance of the system varies. Since real time power system networks are very huge with hundreds of transmission lines, it is not possible to fix these devices with a trial and error method. Also, fixing the FACTS devices at randomly chosen locations may worsen the system performance. Hence this paper proposes two bio-inspired algorithms: PSO and BAT to find an optimal location of these devices so as to improve the system performance. Based on the VCPI metrics, the fitness function for the optimal location is framed as in equation (2)

$$\text{Fitness function} = f_1 * \text{VCPI} + f_2 * \text{Real power loss} + V_p \tag{2}$$

where f_1 and f_2 are constants and V_p is the voltage penalty that is laid on the equation for crossing voltage limits. Constraints including real and reactive power balance, FACTS installation are considered as given in Equations (3)-(6).

$$P_{gi} - P_{di} - \sum_{j=1}^{N} V_j \left[G_{ij} \cos\left(\theta_{ij}\right) + B_{ij} \sin\left(\theta_{ij}\right) \right] = 0 \tag{3}$$

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} V_i \left[G_{ij} \sin\left(\theta_{ij}\right) - Bi_j \cos\left(\theta_{ij}\right) \right] = 0 \tag{4}$$

$$P_{gi} + P_{factsi} = P_{di} + \sum_{j=1}^{n} V_i V_j Y_{ij} \left[\cos\alpha_{ij} + \theta_i + \theta_j \right] \tag{5}$$

$$Q_{gi} + Q_{factsi} = Q_{di} + \sum_{j=1}^{n} V_i V_j Y_{ij} \left[\cos\alpha_{ij} + \theta_i - \theta_j \right] \tag{6}$$

where P_{gi}, Q_{gi}, P_{di} and Q_{di} are the real and reactive power generated and real and reactive power demand, P_{factsi} and Q_{factsi} are the real and reactive powers injected/absorbed by FACTS, V is the voltage, G, B, Y are the conductance, susceptance and admittance of the lines. Cost of FACTS devices is also calculated using the Equations (7)-(8) [11].

$$\text{cost of statcom}\left(\$\right) = \text{Statcom rating in MVar} * 50 \tag{7}$$

$$\text{cost of upfc}\left(\$\right) = 188.2 - 0.2691 * \text{upfc rating} + 0.0003 * \text{upfc rating}^2 \tag{8}$$

3. PSO Based Optimal Location

Particle swarm optimization [18] is a bio-inspired technique, inspired from the intelligent behaviour of a flock of birds moving in search of their food. PSO is a simple algorithm that can solve complex problems, with various boundary conditions in a small time duration. In a PSO algorithm, the swarm interacts in a group which enhances the solution to a problem. Two parameters of a particle: position and velocity, are used as information to travel in the search space. Each particle travels to various locations and saves the value of the best location and velocity obtained so far (Personal best). Similarly a swarm of particles in a society are aware of another value called global best, which is the best value among all personal bests. The position and velocity of each particle is updated for every move, using the equations (9) and (10).

$$v[i+1] = v[i] + \left\{c_1 * rand() * \left(pbest[i] - location[i]\right)\right\} + \left\{c_2 * rand() * \left(gbest - location\ [i]\right)\right\} \tag{9}$$

$$location[i+1] = location[i] + v[i] \tag{10}$$

where v[] is the velocity of the particle, *location*[] is the position of the particle, *pbest* and *gbest* are the personal and global best values. *rand*() is a random number function that generates values between 0 and 1, c_1, c_2 are learning constants, taken as 2.

The procedure to find an optimal location of FACTS devices using PSO is as follows:

Step 1: Initialize the FACTS devices (STATCOM and UPFC) with random position and size (in MVar). Load the system data: line data, bus data, load power is initially set as 100%. Initialize PSO parameters.

Step 2: For each location, evaluate the VCPI value.

Step 3: If the VCPI value is better than the previous values, then the position is updated.
Step 4: The VCPI values from all locations are compared and the best value is set as the global best value.
Step 5: The location and size are updated using the standard PSO position and velocity Equations (9) & (10).
If the value obtained for position is a floating value, then it is rounded off to an integer, as location of FACTS can only be a real number.
Step 6: The process is repeated for a specified number of iterations.
Step 7: The same procedure is again performed for a loading factor of 110% and 120%.

4. BAT Based Optimal Location

BAT [19] is also a bio-inspired algorithm based on the echo location behaviour of microbats. They emit a loud voice and listens for the echo from the surroundings, thereby detecting prays and avoiding obstacles. Similar to the PSO algorithm, BAT algorithm also has two parameters: the position (*location*[]) and velocity (*v*[]) of bats. The equation used to determine these values are given in (11) and (12).

$$v[i+1] = v[i] + \left(location[i] - location^{*}\right) f[i] \tag{11}$$

$$location[i+1] = location[i] + v[i+1] \tag{12}$$

where

$$f[i] = f_{\min} + \left(f_{\min} - f_{\max}\right)\beta \tag{13}$$

and $location^{*}$ is the global best location of all the bats in the search space. '*f*' is the frequency assigned to each bat, and β is a random vector of (0,1), generated from a uniform distribution. To obtain a new solution for the bats, random walk is used as in equation (14).

$$location[new] = location[old] + \epsilon A^{t} \tag{14}$$

where ϵ is a random number between (−1, 1) and *A* is the average loudness of all the bats. This local search differentiates BAT from PSO algorithm. FACTS optimal location can be found using BAT algorithm with the following procedure:

Step1: Initialize the FACTS devices (STATCOM and UPFC) with random position and size (in MVar). Load the system data: line data, bus data, load power is initially set as 100%.
Step2: Initialize BAT parameters, frequency, and loudness (Ai), rand and pulse rate ri.
Step3: For each location, calculate the fitness value VCPI.
Step4: Update the position and velocities using relevant equations and frequencies.
Step5: if (rand > ri).
Select a solution among the best solutions.
Generate a local solution around the selected best solution.
Step6: if (rand < ri).
Generate a new solution by flying randomly.
Step7: if (rand < Loudness & f(location[i]) < f(location∗)).
Accept the new solutions Increase ri and reduce Ai.
Step8: Rank the bats and find the current best location∗.

5. Results and Discussions

The proposed algorithms are tested on the IEEE 118 bus system and the Indian Uttar Pradesh State Electricity Board 75 bus system. The parameter settings of PSO are given in **Table 1** and that of BAT in **Table 2**.

5.1. Case Study 1: IEEE 118 Bus System

The IEEE 118 bus system consists of 19 generators, 35 synchronous condensers, 177 lines, 9 transformers and 91 loads. The system is simulated under three loading conditions: full load, 110% and 120% of full load, with PSO and BAT algorithms. The VCPI index, real power loss and sizing of the FACTS devices are calculated along with the identification of weak bus (**Table 3**). Under all loading conditions, PSO performs better than BAT algorithm. The VCPI index of the system without installing FACTS device is 0.4632. With the installation

Table 1. PSO parameters.

Parameter	Value
Population size	20
C1	1.5
C2	2.5
Inertia	0.3
Damp ratio	0.95
Iterations	30

Table 2. BAT parameters.

Parameter	Value
Population size	20
A	0.5
r	0.5
Fmin	0
Fmax	2
Iterations	30

Table 3. IEEE 118 system.

Loading	Algorithm	Parameters									
		VCPI	Weak line	UPFC			STATCOM			Real power loss (MW)	Time (s)
				Location	Size Voltage angle	Cost (US $/kVAr)	Location	Size MVar	Cost (US $/kVAr)		
100	**No FACTS**	0.4632	105			-				5097	-
	PSO	0.3506	105	82 - 83	0.235 2.999	135	85	4.7	62.42	3089	879
	BAT	0.3756	105	50 - 57	0.208 0.679	183	57	2.095	188.0	3392	5432
110	**No FACTS**	0.4998	105			-				5632	-
	PSO	0.3875	105	114 - 115	0.567 0.457	183	28	3.77	124.6	3572	854
	BAT	0.3936	105	94 - 95	0.233 2.447	188	39	0.848	199.3	3683	5120
120	**No FACTS**	0.5695	105			-				5913	-
	PSO	0.4261	31	114 - 115	0.210 3.000	184	40	3.77	205	3788	897
	BAT	0.4592	39	114 - 115	0.300 0.00	188	6	3.786	250.5	3994	5876

of FACTS using PSO, there is a reduction of VCPI by 24.3% and with BAT algorithm by 18.9%. Similarly the real power loss of the system is 5097 MW, which is 39.4% and 33.4% more when compared to the system with optimally located FACTS device using PSO and BAT respectively.

The algorithms are run for 100 times with the same input conditions and the best, worst and mean values are given in **Table 4**.

5.2. Case Study 2: UPSEB 75 Bus System

The UPSEB 75 bus system is an Indian Utility system of the state of Uttar Pradesh in India. It includes 15 generators and 98 transmission lines [20]. The results with all types of loading conditions are given in **Table 5**. The VCPI value without installation of FACTS device is 0.8364. By optimally locating FACTS devices using PSO and BAT techniques, the VCPI value is reduced to 11.1% and 7.5% respectively. The real power losses are also reduced by 79.5% using FACTS devices with PSO and 79% using BAT when compared to the system before installation of FACTS (5126 MW). PSO algorithm also obtains the results faster when compared to BAT algorithm.

PSO and BAT algorithms are tested 100 times for each loading conditions and their best, worst and average values are tabulated in **Table 6**.

The convergence characteristics of PSO and BAT are given in **Figure 3**. PSO is seen to converge faster than BAT algorithm. A comparison of voltage profile and VCPI values of each bus obtained using the algorithms is given in **Figure 4** and **Figure 5**. It is observed that PSO performs better than BAT in maintaining the voltage values at 1 p.u. and in decreasing the VCPI values, thereby improving the stability of the system.

Table 4. Output of multiple runs.

Values	Loading					
	100%		110%		120%	
	PSO	BAT	PSO	BAT	PSO	BAT
Best	0.3485	0.3700	0.3821	0.3855	0.4155	0.4501
Mean	0.3506	0.3756	0.3875	0.3936	0.4261	0.4592
Worst	0.3598	0.3799	0.3934	0.4003	0.4376	0.4711

Table 5. UPSEB 75 bus system.

Loading	Algorithm	Parameters									
		VCPI	Weak line	UPFC			STATCOM			Real power loss (MW)	Time (s)
				Location	Size Voltage angle	Cost (US $/kVAr)	Location	Size MVar	Cost (US $/kVAr)		
100	**No FACTS**	0.8073	24			-				5126	-
	PSO	0.7436	24	38 - 39	0.387 0.960	143	69	0.63	31	1048	477
	BAT	0.7470	24	36 - 37	0.400 0.000	177	75	4.76	238	1071	2908
110	**No FACTS**	0.8204	24			-				5814	-
	PSO	0.7581	24	19 - 20	0.400 0.000	177	64	2.96	148	1072	494
	BAT	0.7598	6	45 - 44	0.361 1.882	184	49	4.98	249	1109	3108
120	**No FACTS**	0.8364	24			-				5906	-
	PSO	0.7958	24	19 - 20	0.393 0.047	179	74	3.32	166	1241	473
	BAT	0.8145	6	19 - 20	0.142 0.428	186	75	5.00	250	1530	3402

Table 6. Robustness measure.

Values	Loading					
	100%		110%		120%	
	PSO	BAT	PSO	BAT	PSO	BAT
Best	0.7424	0.7329	0.7330	0.7218	0.7743	0.8108
Mean	0.7436	0.7470	0.7581	0.7598	0.7958	0.8145
Worst	0.7518	0.7698	0.7789	0.7983	0.7963	0.8198

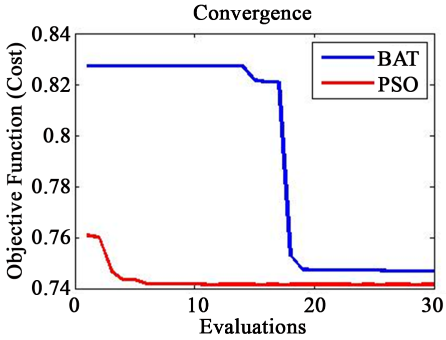

Figure 3. Convergence characteristics of PSO and BAT.

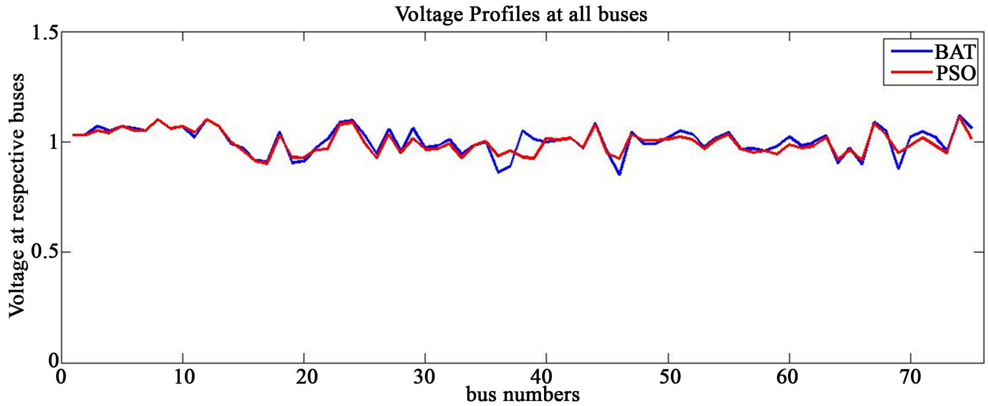

Figure 4. Voltage profile at all bus.

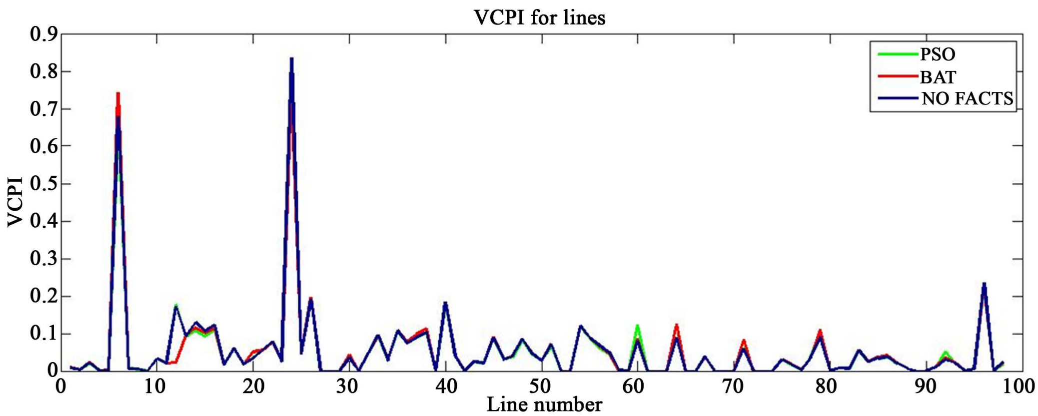

Figure 5. VCPI at each bus.

6. Conclusion

Particle swarm optimization and BAT algorithms are successfully used to find a suitable location of multi-type FACTS devices. UPFC and STATCOM, that can perform better than other FACTS devices, are chosen and modeled using power injection model with Jacobian matrix representation. The proposed system is tested on the MATLAB environment using two test cases, IEEE 118 and UPSEB 75 bus system, to validate the proposed objective. Installation of FACTS at appropriate locations using PSO and BAT reduces the VCPI index and real power losses by 18% and 60% on an average. Installation of FACTS devices optimizes the power system, but is made more reliable with proper choice of location. PSO algorithm is found to provide better results when compared to BAT algorithm in all aspects.

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