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Multi-type FACTS placement for loss minimization using biogeography based optimization

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Abstract: This paper presents a new strategy for optimal placement of multi-type FACTS devices with a view to minimize losses besides enhancing the voltage profile using biogeography based optimization. The strategy places three types of FACTS devices that include static VAR compensator, thyristor controlled series compensator and unified power flow controller; and offers optimal locations for placement, type and parameters of the FACTS devices. Test results on IEEE 14, 30 and 57 bus systems reveal the superiority of the algorithm.

Key words: biogeography based optimization, FACTS devices

Nomenclature: BBO – biogeography based optimization; $E^{\max}$ – maximum emigration rate; FACTS – flexible AC transmission systems; GA – genetic algorithm; g_k – conductance of the transmission line-k; *HSI* – habitat suitability index; $I^{\max}$ – maximum immigration rate; $Iter^{\max}$ – maximum number of iterations; L_k – number of a line, where k^{th} FACTS device is to be located; $m^{\max}$ – maximum mutation rate; $m(s)$ – mutation rate for habitat possessing S species; nf – number of FACTS devices; nh – number of habitats; nl – number of transmission lines; *nload* – number of load buses; n – total number of species in the habitat; *neh* – number of elite habitats; PSO – particle swarm optimization; PM – proposed method; P_L – system real power loss; $P^s(t)$ – probability that the habitat contains exactly S species at time t; P^s – species count probability; P^{mod} – habitat modification probability; $P^{\max}$ – maximum probability; P_{ij} and Q_{ij} – active and reactive power flow from bus- i to j respectively; $P(V,\delta)$ – set of real power expressions at PV and PQ buses; P^{sp} – set of specified real powers at PV and PQ buses; $Q(V,\delta)$ – set of reactive power expressions at PQ buses; Q_{Gi} – reactive power generation at bus-i; Q^{sp} – set of specified reactive powers at PQ buses; $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ – lower and upper limit reactive power generation at bus-i respectively; Q_{Fk} – reactive power support by k^{th} FACTS device in MVAR; S – species in the habitat; $S^{\max}$ – maximum species in the habitat; S_i –

apparent power flow through line-i; S_{Li} – apparent power flow violation at line-i; $S_i^{\max}$ – apparent power flow limit of line-i; SVC – static VAR compensator; SIV – suitability index variable; STATCOM – static synchronous compensator; SSSC – static synchronous series compensator; TCPAR – thyristor controlled phase angle regulator; TCSC – thyristor controlled series compensator; T_k – type of k^{th} FACTS device; UPFC – unified power flow controller; V_i and V_j – voltage magnitude at buses -i and j respectively; $V_i^{\min}$ and $V_i^{\max}$ – lower and upper limits voltage magnitude at bus-i respectively; V_{di} – voltage deviation at bus-i; w_1 w_2 and w_3 – weight constants; x_{ij} – reactance of the transmission line between buses-i and j; λ and μ – immigration and emigration rates respectively; Ψ_v and Ψ_s – constants; δ_{ij} – voltage angle between buses-i and j; x_{ij}' – net reactance of the transmission line between buses-i and j; along with FACTS device; x_F – reactance of the FACTS device; η_k – line compensation factor in the range of (-0.8, 0.2) for k^{th} FACTS device; ΔQ_i – change in reactive power injection at bus-i by a FACTS device; subscript i and j – terminal buses of line-k.

1. Introduction

The present day power system is a large complex interconnected network that consists of thousands of buses and hundreds of generators. The network is expanding everyday with the increase in demand and to meet this situation, either new installation of power generating stations and transmission lines is required or the existing infrastructure operation has to be extended to limits. The laying of new lines or installation of new generating stations imposes many environmental and economical constraints. As a result, the existing transmission lines are more heavily loaded than ever before. In steady state operation of heavily loaded power systems, the main problems are increased losses, poor voltage profile, unwanted loop flows and line overloads. Optimal real and reactive power dispatch and the installation of reactive power sources at appropriate buses can minimize the losses and enhance the voltage profile. The other problems require control over line parameters.

The recent developments in power electronics have introduced Flexible AC Transmission Systems (FACTS) that include Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Phase Angle Regulator (TCPAR) etc., These devices can facilitate the control of power flow, increase the power transfer capability, decrease the generation cost, improve the security and enhance the stability of the power systems. They allow the operation of the power systems more flexible, secure and economical through controlling various electrical parameters of transmission circuits. However, the decision on the size, the locations and their parameters is of great significance in obtaining the benefits of the FACTS devices [1, 2].

The placement of FACTS devices can be described as an optimization problem with an objective of minimizing a cost function while satisfying system constraints. The objective of this problem may be to reduce the power loss, minimize the fuel cost, lower the installation cost, minimize the voltage magnitude deviation and maximize the voltage stability margin.

The constraints may include power flow and security limits under normal and contingent conditions. Owing to rigorous constraints, the FACTS placement problem may be a non-convex and nonlinear problem, and becomes the most challenging optimization problem in power systems.

Numerous methods for obtaining the solution of FACTS placement problem have been suggested in the recent years [3-12]. A particle swarm optimization (PSO) based algorithm for reactive power and voltage control in order to ensure voltage security has been suggested in [3]. An operation scheme based on UPFC in order to ensure security through line over load control and low voltage control has been notified in [4]. A method for installing UPFC with a view of enhancing VS margin under contingent conditions has been briefed in [5]. A bacterial foraging based solution algorithm using UPFC for loss minimization and voltage stability limit improvement has been outlined in [6]. An adoptive immune algorithm for the reactive power optimization has been outlined in [7]. An analytical procedure for minimizing voltage deviations in order to indirectly enhance VS through reactive power compensation has been narrated in [8]. Several methods for prevention of voltage instability using FACTS devices in power systems have been surveyed in [9]. An operation strategy involving SVCs for improving voltage profile and minimizing real power loss reduction has been suggested in [10]. A strategy for maintaining reactive power reserve with a view of avoiding voltage collapse has been presented in [11]. An optimal allocation method for FACTS devices for market based power system considering congestion relief and voltage stability has been proposed in [12].

The solution techniques may be classified as conventional methods, intelligent searches and fuzzy set applications. The conventional methods include linear programming, nonlinear programming, mixed-integer nonlinear programming, etc. The intelligent-search-based methods such as simulated annealing, genetic algorithm (GA), evolutionary algorithm and PSO have received widespread attention as possible techniques to obtain the global optimum solution. The fuzzy set theory has been applied to address uncertainties in objectives and constraints. In the light of the fact that there are no known ways to find the exact global solution for this complicated optimization problem, there is always a need to develop better methods with a view of obtaining the global best solution.

Recently, a biogeography based optimization (BBO) algorithm has been suggested for solving optimization problems [13]. It is based on the mathematics of biogeography that studies the geographical distribution of biological organisms. In this approach, problem solutions are represented as islands or habitats and the sharing of features between solutions is represented as immigration and emigration between islands. It has been applied to several optimization problems such as optimal reactive power control [14], economic load dispatch [15] and power flow [16].

An elegant strategy for optimal placement of multi-type FACTS devices using BBO is proposed in this paper. The algorithm is tested on IEEE 14, 30 and 57 bus test systems and the results are presented. The paper is divided into six sections. Section 1 provides the introduction, Section 2 describes the BBO algorithm, Section 3 overviews the modeling of FACTS devices, Section 4 elucidates the proposed method (PM), Section 5 discusses the results and Section 6 furnishes the concluding remarks.

2. Biogeography-based optimization

BBO, suggested by Dan Simon in 2008, is a stochastic optimization technique for solving multimodal optimization problems. It is based on the concept of biogeography, which deals with the distribution of species that depend on different factors such as rain fall, diversity of vegetation, diversity of topographic features, land area, temperature, etc. A larger number of species are found in favorable areas compared with that of a less favorable area. A habitat is defined as an island that is geographically isolated from other areas. The areas that are well suited as residents for species are said to have high Habitat Suitability Index (HSI). The variables that characterize habitability are called suitability index variables ($SIVs$). The large number of species on high HSI islands has many opportunities to emigrate into neighboring habitats with less number of species and share their characteristics with those habitats. For this reason, habitats with low HSI have a high species immigration rate. The immigration and emigration process helps the species in the area with low HSI to gain good features from the species in the area with high HSI and makes the weak elements into strong. Besides it allows retaining good features of species in the area with high HSI. The rate of immigration (λ) and the emigration (μ) are the functions of the number of species in the habitat. Figure 1 shows the immigration and emigration curves indicating the movement of species in a single habitat.

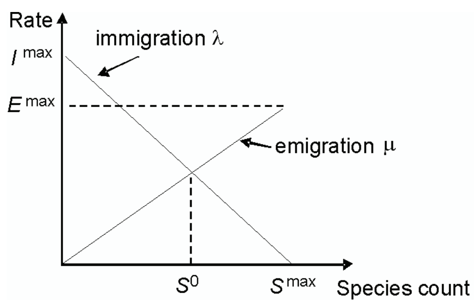

Fig. 1. Species model of single habitat

In BBO, a good solution is referred to an island with high HSI and a poor solution to an island with low HSI. The poor solutions in islands with low HSI accept a lot of new features from good solutions in islands with high HSI and improve their quality. However, the shared features of the good solution still remain in the high HSI solutions. The concept of immigration and emigration is mathematically represented by a probabilistic model, which relates the probability $P^s(t)$ that a habitat contains exactly S species at time t with that of the probability $P^s(t+\Delta t)$ at time $(t+\Delta t)$, as

$$P^s(t+\Delta t) = P^s(t)\,(1-\lambda_s\,\Delta t-\mu_s\,\Delta t)+P^{s-1}\,\lambda_{s-1}\,\Delta t+P^{s+1}\,\mu_{s+1}\,\Delta t\,. \tag{1}$$

If time Δt is so small that the probability of more than one immigration or emigration can be ignored then taking the limit of Equation (1) as $\Delta t \rightarrow 0$ gives the following equation:

$$\dot{P}^{s} = \begin{cases} -(\lambda_s + \mu_s)P^s + P^{s+1}\ \mu_{s+1} & S = 0 \\ -(\lambda_s + \mu_s)P^s + P^{s+1}\ \mu_{s+1} + P^{s-1}\ \lambda_{s-1} & 1 \le S \le S^{\max} \\ -(\lambda_s + \mu_s)P^s + P^{s-1}\ \lambda_{s-1} & S = S^{\max} \end{cases}. \tag{2}$$

The equation for emigration rate μ_k and immigration rate λ_k for k-number of species is developed from Figure1 as

$$\mu_k = \frac{E^{\max}}{n}, \tag{3}$$

$$\lambda_k = I^{\max}\left(1 - \frac{k}{n}\right), \tag{4}$$

when $E^{\max} = I^{\max}$, the immigration and emigration rates can be related as:

$$\lambda_k + \mu_k = E^{\max}. \tag{5}$$

The concept of BBO is based on the mechanisms of migration and mutation as discussed below.

2.1. Migration

A population of candidate solutions can be represented as vectors of real numbers in BBO algorithm. Each real number in the array is considered as a SIV, which is then used to evaluate the fitness of each candidate solution, denoted by HSI. High HSI represents a better quality solution and low HSI denotes an inferior solution. The emigration and immigration rates of each solution are probabilistically used to control the sharing of features between habitats through a habitat modification probability, P^{mod}. If a given solution S_i is selected for modification, then its λ is used to probabilistically decide whether or not to modify each SIV in that solution. After selecting the SIV for modification, μ of other solutions are used to select which of the solutions among the habitat set will migrate randomly chosen $SIVs$ to the selected solution S_i. Some kind of elitism, which retains the best habitat having highest HSI without performing migration operation, is used in order to prevent the best solutions from being corrupted.

2.2. Mutation

The cataclysmic events that drastically change the HSI of a habitat is represented by mutation of SIV and species count probabilities are used to determine mutation rates. The probability of each species count, P^s given by Equation (2), indicates the likelihood that it exists as a solution for a given problem. If the probability of a given solution is very low, then that solution is likely to mutate to some other solution. Similarly if the probability of some solution is high, then that solution has very little chance to mutate. So, it can be said that very high HSI solutions and very low HSI solutions have less chance to create more improved SIV in the later stage. But the medium HSI solutions have better chance to create much better solutions after mutation operation. Mutation rate of each set of solution can be calculated in terms of species count probability using the following equation:

$$m(S) = m^{\max}\left(\frac{1-P^{s}}{P^{\max}}\right). \tag{6}$$

This mutation scheme tends to increase diversity among the population, avoids the dominance of highly probable solutions and provides a chance of improving the low HSI solutions even more than they already have.

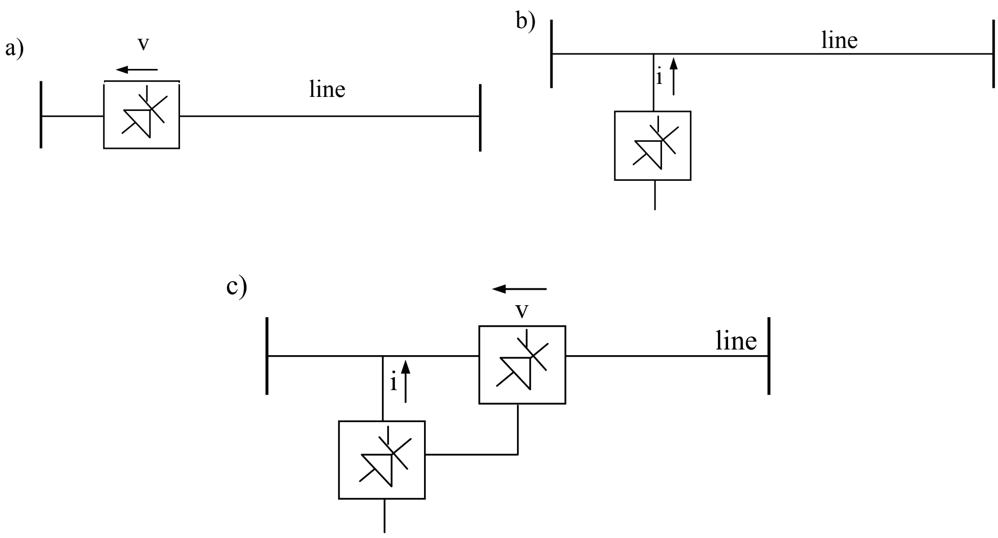

Fig. 2. Basic type of FACTS devices: a) series controllers; b) shunt controllers; c) series and shunt controllers

3. FACTS devices

The FACTS devices that are solid state converters can be categorized into series, shunt and combined series-shunt controllers as shown in Figure 2. The series controllers inject voltage in series with the line and the shunt controllers add current into the system. The combined series and shunt controllers inject both voltage and current into the system [1]. Table 1 lists the representative kinds of FACTS devices with controllable parameters [2].

Table 1. Types of FACTS devices

Type of controllers	Controlled parameter	FACTS devices
series	series P	TCSC, SSSC, TCPAR
shunt	shunt Q	SVC, STATCOM
combined series and shunt	series P and shunt Q	UPFC

Several FACTS devices are available and each one has its own properties. The choice of the appropriate device is important in order to reach the desired goals. Three different FACTS devices modeled for steady state analysis, one from each type, with specific characteristics are selected to place them at suitable locations in order to control active power flows and reactive power injections in the PM. They are SVC, TCSC and UPFC. Only one type of FACTS device may be allowed at each line/bus. Besides a limited number of devices, beyond which the improvement of the chosen objectives may not be significant, are usually installed.

3.1. FACTS modeling

The active and reactive power flow from bus i to j through transmission line-m may be approximated by the following equations

$$P_{ij} = \frac{V_i V_j}{x_{ij}} \sin \delta_{ij}, \tag{7}$$

$$Q_{ij} = \frac{1}{x_{ij}} (V_i^2 - V_i V_j \cos \delta_{ij}). \tag{8}$$

Under normal operating conditions for high voltage transmission systems, the voltage at any two buses are approximately equal and the voltage angle difference between any two buses are very small, which decouples the active and reactive power flow through any line. Active and reactive power flows depend only on the voltage angle difference and voltage magnitude difference respectively. However, both of them can be controlled by varying the line reactance.

TCSC acts either as a capacitive or inductive compensator by modifying the reactance of the transmission line, thereby changes line flow. The net reactance x_{ij}' of the transmission line-m, connected between buses i and j, after inclusion of TCSC can be written as

$$x_{ij}' = x_{ij} + x_F, \tag{9}$$

where: $x_F = \eta\, x_{ij}$ the reactance of the FACTS device; η line compensation factor in the range of (−0.8, 0.2) to avoid overcompensation.

The SVC is shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of electrical power system, typically a bus voltage. The change in reactive power at bus-i with SVC can be represented as

$$\Delta Q_i = Q_F. \tag{10}$$

UPFC consists of two converters. The series converter injects a voltage that alters the line reactance, thereby controls active power flow and the shunt converter independently supplies or absorbs the reactive power. It can be modeled for convenience as a combination of SVC and TCSC through Equations 9 and 10.

4. Proposed strategy

Appropriate FACTS devices should be installed at the best possible locations with optimal parameter settings in order to reduce the system real power losses. The FACTS placement problem is formulated as an optimization problem involving losses as

Minimize
$$P_L = \sum_{k=1}^{nl} g_k \left(V_i^2 + V_j^2 - 2\,V_i\,V_j \cos\delta_{ij}\right). \tag{11}$$

Subject to

FACTS device constraints

$$-0.8 \le \eta_k \le 0.2 \quad \text{for TCSC,} \tag{12}$$

$$-100\,MVAR \le Q_{Fi} \le +100\,MVAR \quad \text{for SVC,} \tag{13}$$

$$\text{Eqs. (12) and (13)} \quad \text{for UPFC.} \tag{14}$$

Power flow constraints

$$P(V,\delta) - P^{sp} = 0 \quad \text{for PV and PQ buses,} \tag{15}$$

$$Q(V,\delta) - Q^{sp} = 0 \quad \text{for PQ buses.} \tag{16}$$

Reactive power generation constraints at PV buses

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad \text{for PV buses.} \tag{17}$$

Voltage constraints at PQ buses

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \text{for PQ buses.} \tag{18}$$

Line flow constraints

$$S_i \le S_i^{\max} \quad \text{for all lines.} \tag{19}$$

4.1. Representation of BBO variables

Each island in the PM is defined to denote the type of the devices, their locations and parameters in matrix form as shown in Figure 3.

T_1	T_2	T_3	$\cdots$	T_{nf}
L_1	L_2	L_3	$\cdots$	L_{nf}
η_1	η_2	η_3	$\cdots$	η_{nf}
${Q_F}^1$	${Q_F}^2$	${Q_F}^3$	$\cdots$	${Q_F}^{nf}$

Fig. 3. Representation of decision variables

The first row contains integer numbers in the range of (1-3) and represents the type T_k of the FACTS devices. In this formulation, 1 represents SVC, 2 denotes TCSC and 3 indicates UPFC. The second row corresponds to the location of the devices. It represents the numbers of the line L_k where the devices are to be located. The shunt devices are connected at the starting bus of the chosen line. The third and fourth rows correspond to line compensation factor η_k and injected reactive power Q_F^k respectively. The parameter that is not required for a particular type of device is ignored. The problem variables contain both integer value for representing T_k and L_k and real values to denote η_k and Q_F^k but the BBO algorithm deals with real numbers. Therefore, the values in the first two rows are rounded off to the nearest integer values.

4.2. Repair algorithm

It is undesirable to fix two or more FACTS devices at a line/bus. During the iterative process, there is a possibility that a solution point contains same line numbers in the second row of Figure 3. If this happens, it may be corrected by the following repair mechanism.

- Alter any one line number by generating a random number to represent another line.
- Repeat the above step till no two numbers in the second row is same.

4.3. Fitness function

The solution of the island can be limited to satisfy the constraints of Equations 12-14 and the constraints of Equations 15-17 are taken care of by the load flow algorithm during the search process. The constraint on bus voltages at load buses of Equation (18) and flow at all lines of Equation (19) can only be controlled through penalizing the problem objective, if they violate. The augmented objective function that blends both the problem objective and the load voltage and line flow constraints, is formulated as

$$\text{Minimize} \quad \Phi = w_1\, P_L + w_2 \sum_{i=1}^{nload} V_{di} + w_3 \sum_{i=1}^{nl} S_{Li}, \tag{20}$$

where:

$$V_{di} = \begin{cases} 0 & \text{if } V_i \in \left[V_i^{\min}, V_i^{\max}\right] \\ \exp\left\{\Psi_v\left(\left|1-V_i\right|-0.05\right)\right\}-1 & \text{if } V_i \notin \left[V_i^{\min}, V_i^{\max}\right], \end{cases} \tag{21}$$

$$S_{Li} = \begin{cases} 0 & \text{if } S_i \le S_i^{\max} \\ \exp\left\{\left(S_i^{\max} - S_i\right) / \Psi_s\right\} - 1 & \text{if } S_i > S_i^{\max} \end{cases} . \tag{22}$$

The value of V_{di} equals to zero if the voltage magnitude falls between the lower and upper voltage limits. Outside the range, it increases exponentially with the voltage deviations. Similarly S_{Li} increases exponentially, if the line flow exceeds the respective line flow limit. The coefficient Ψ_v and Ψ_s are used to adjust the slope of the exponential function.

The BBO searches for optimal solution by maximizing a fitness function, denoted by HSI, which measures the quality of the solution of an island. The HSI is problem dependant and obtained by suitably converting the objective function into a maximization function as

$$\text{Maximize} \quad HSI = \frac{1}{1+\Phi} . \tag{23}$$

The penalty term reduces the HSI of the island depending on the magnitude of the violation. This penalty approach does not disregard infeasible solutions; instead it uses these solutions in such a way as to aid the search process. Sometimes these infeasible solutions may provide much more useful information about the optimum than the feasible solutions.

4.4. Stopping criterion

The process of generating new population can be terminated either after a fixed number of iterations or if there is no further significant improvement in the global best solution.

4.5. Solution process

An initial population of habitats is obtained by generating random values within their respective limits to every individual in the population. The HSI is calculated by considering $SIVs$ of each habitat and the migration and mutation operations are performed for non-elite habitats with a view of maximizing the HSI. The iterative process is continued till convergence. The flow of the PM is shown in Figure 4.

5. Simulations

The proposed BBO based strategy is tested on IEEE 14, 30 and 57 bus test systems. NR technique [17] is used to carry out the load flow during the optimization process. The MVA flow limit of each line is set to be 125% of the initial flow. The results of the PM are compared with that of GA and PSO based approaches for all the three test systems with a view to demonstrate the effectiveness. The PM is initially run with different number of FACTS devices with a view to choose the optimal number of FACTS devices for all the systems and the resulting loss is presented in Table 2.

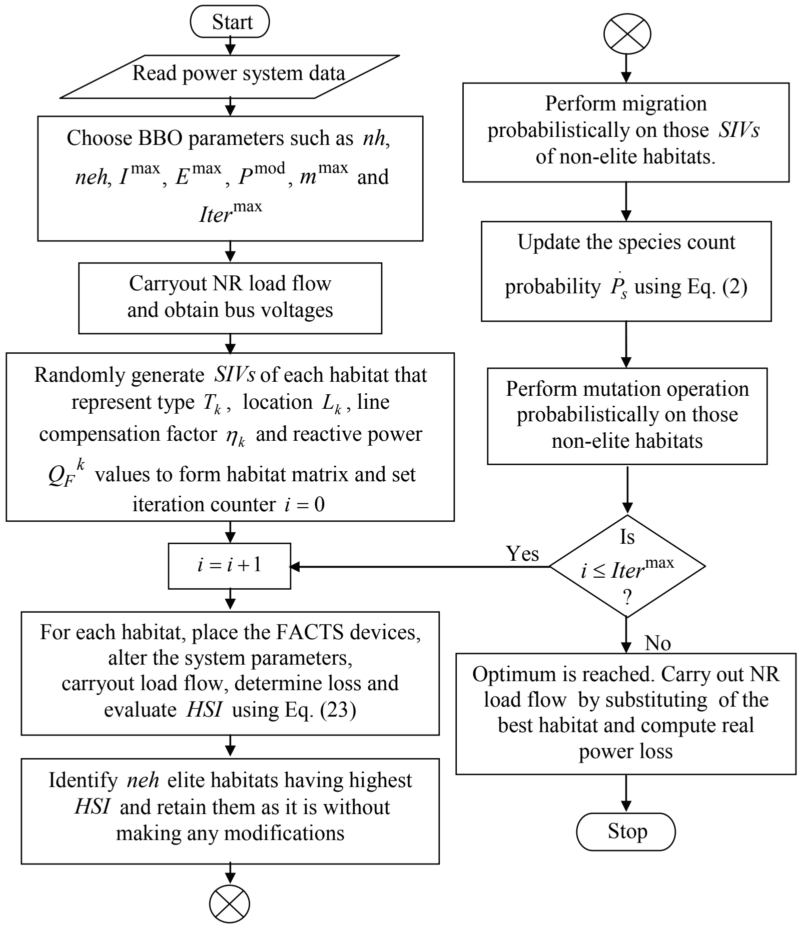

Fig. 4. Flow chart of the PM

It can be observed from this table that the loss can be considerably reduced from 0.1337 per unit to 0.1315 per unit, when five FACTS devices are connected for IEEE 14 bus system. If the nf is further increased by one, the loss savings is insignificant. The nf for the present study is therefore chosen as 5 for IEEE 14 bus systems. Similarly for IEEE 30 and 57 bus systems, it is selected as 7 and 8 respectively.

The type, locations and their parameters are given in Table 3 for IEEE 14 bus system. The PM requires one SVC, two TCSCs and three UPFCs at line locations 9, 17, 10, 11 and 13. The PSO based approach demands one SVC, one TCSC and three UPFCs at lines of 20, 17, 9, 8 and 11. The GA based strategy requires two SVCs and four UPFCs at lines of 20, 17, 9, 8 and 11. The type, locations and their parameters are given in Tables 4 and 5 for IEEE 30 and 57 bus systems respectively.

Table 2. Network Loss with number of FACTS devices

System	nf	P_L (per unit)
IEEE 14	0	0.1337
	2	0.1329
	3	0.1324
	4	0.1319
	5	**0.1315**
	6	0.1316
IEEE 30	0	0.0761
	4	0.0831
	5	0.0724
	6	0.0713
	7	**0.0699**
	8	0.0697
IEEE 57	0	0.2839
	5	0.2684
	6	0.2622
	7	0.2582
	8	**0.2569**
	9	0.2570

Table 3. Optimal solution obtained for IEEE 14 bus system

PM	T_k	2	3	2	3	1
	L_k	9	17	10	11	13
	η_k	−0.089	0.084	0.058	−0.355	–
	Q_F^k	–	0.289	–	−0.539	0.277
PSO	T_k	3	3	2	1	3
	L_k	20	17	9	8	11
	η_k	−0.761	−0.062	0.017	–	−0.714
	Q_F^k	0.087	0.329	–	−0.214	−0.766
GA	T_k	1	3	3	1	3
	L_k	20	17	9	8	11
	η_k	–	0.124	−0.099	–	−0.360
	Q_F^k	0.088	0.386	0.697	−0.225	−0.824

Table 4. Optimal solution obtained for IEEE 30 bus system

PM	T_k	2	1	3	1	1	2	3
	L_k	10	36	13	11	29	41	4
	η_k	0.021	–	0.018	–	–	−0.094	−0.378
	Q_F^k	–	0.202	0.110	−0.926	0.178	–	−0.286
PSO	T_k	2	1	3	1	1	2	3
	L_k	10	29	13	12	38	41	17
	η_k	0.021	–	0.018	–	–	−0.184	0.199
	Q_F^k	–	0.180	0.004	−0.901	0.185	–	−0.140
GA	T_k	2	3	3	1	1	2	3
	L_k	10	24	13	12	37	41	17
	η_k	0.021	−0.335	0.018	–	–	−0.218	0.199
	Q_F^k	–	0.048	0.004	−0.692	0.185	–	−0.223

Table 5. Optimal solution obtained for IEEE 57 bus system

PM	T_k	3	1	2	2	3	2	3	1
	L_k	69	41	74	52	53	64	49	67
	η_k	0.015	–	0.084	0.191	−0.122	0.199	−0.648	–
	Q_F^k	−0.219	0.140	–	–	0.208	–	0.164	0.104
PSO	T_k	3	3	2	1	2	2	1	1
	L_k	69	41	64	60	53	71	47	67
	η_k	−0.797	−0.570	0.191	–	−0.300	0.119	–	–
	Q_F^k	−0.139	0.071	–	0.091	–	–	0.292	0.133
GA	T_k	2	2	2	1	2	2	1	1
	L_k	69	41	74	34	53	71	50	67
	η_k	−0.792	−0.720	−0.027	–	−0.233	0.040	–	–
	Q_F^k	–	–	–	0.292	–	–	0.323	0.075

The performance in terms of loss, lower and upper voltage magnitude at load buses before and after placement of FACTS devices are given in Table 6. The results indicate that the PM offers the lowest loss compared to that of GA and PSO based strategies besides offering better voltage profile. The simulation study also indicates that none of the line flow violates the respective line flow limits for all the test cases. The various parameters used in the BBO algorithm are listed in Table 7. It is very clear from the results that the PM reduces system losses in addition to bringing the load bus voltages within the allowable range and makes it suitable for practical implementations.

Table 6. Comparison of results before and after FACTS placement

System	V^{low}/V^{high}				P_L			
	before	after			before	after		
		PM	PSO	GA		PM	PSO	GA
14	1.0104/1.0384	0.9732/1.0019	0.9831/1.0213	0.9689/1.0209	0.1337	0.1315	0.1325	0.1326
30	0.9988/1.0802	0.9507/1.0358	0.9502/1.0172	0.9517/1.0037	0.0761	0.0699	0.0701	0.0702
57	0.8306/1.0174	0.9499/1.0174	0.9500/1.0175	0.9500/1.0175	0.2839	0.2569	0.2602	0.2604

Table 7. BBO Parameters

Parameters	Chosen value
nh	50
neh	2
$I^{\max}$	1
$E^{\max}$	1
P^{mod}	0.96
$m^{\max}$	0.08
$Iter^{\max}$	1000

6. Conclusion

BBO optimization method is a natural based optimization technique possessing the characteristics of PSO and GA which are also the natural based optimization techniques. A new BBO based algorithm for reducing the losses by placing multi-type FACTS devices at most appropriate buses has been developed. The algorithm determines the type, the locations and their parameters. The simulation results have clearly illustrated that the PM offers enhanced performance in terms of lower losses. It follows that this formulation exploits the capability of BBO and will culminate it as a powerful tool in solving FACTS placement problem.

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