The Placement of FACTS Devices in Modern Electrical Network Using Bees Algorithm

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Abstract: - This paper presents a Bees Algorithm (BA) to seek the optimal allocation of FACTS devices in deregulated power system. The optimizations are made on three parameters: the location of the devices, their types and their sizes. The FACTS devices are located in order to enhance the available transfer capability (ATC) between source and sink area. Four types of FACTS controllers are used and modeled for steady state studies, namely; TCSC, SVC, UPFC and TCPST. Simulations are performed on an IEEE118 bus power system for single and multi-type FACTS devices. A Genetic Algorithm (GA) configured to the same purpose is used for validation. Results show the difference of efficiency of the devices used in this situation. They also show that simultaneous use of several kinds of controllers is the most efficient solution to increase the ATC. The results also indicate that a Bees Algorithm can be competently used for nonlinear optimization with faster convergence compared to GA.

Key-Words: - Bees Algorithm, GA, ATC, FACTS, SVC, UPFC, TCPST, TCSC

1 Introduction

The electric industry around the world is enduring a radical paradigm move towards deregulation. Due to competition among utilities and contracts between producers and consumers in modern network, unplanned power exchanges increases. Transmission congestion may occur if these exchanges are not controlled and well planned. In a deregulated environment, this sort of control is subject to ancillary services market. Thus, it is in the attention of the Transmission System Operator (TSO) to acquire another way of controlling power in order to permit a more efficient and secure use of transmission lines.

The FACTS devices (Flexible AC Transmission Systems) allows the system operator to control the power flows as desired and has the potential to improve line transfer capability up to its thermal limits [1]. These devices may be used for power flow control, as well as the voltage control with their ability to change the apparent impedance of a transmission line. Because of this, these devices are believed to be one of key solution to congestion problems. However, in economical point of view, careful planning is required before it is installed in the system because the benefit also comes with high financial cost. With this reason, the optimal placement is one of the most popular and main researches on these devices. With the aim to obtain the highest benefit from them.

The above quoted benefits can only be achieved efficiently by some of a given kind of FACTS devices. Hence, in order to reach the required goals, it is important to choose the suitable type of FACTS devices. In this paper, optimal location of different kind of FACTS devices will be analyzed with specific characteristics. They are modeled for steady state analysis, and located in order to maximize the available transfer capability between the sources and sink area. Thus, attention is paid in this current work to study a technique to optimally allocate the devices to enhance ATC.

The task of calculating ATC is one of main concerns in power system operation and planning [2]. ATC is determined as a function of increase in power transfers between different systems through prescribed interfaces. In this research, the ATC is calculated using Repetitive Power Flow (RPF) and the effectiveness of the devices to enhance ATC is investigated using IEEE118 bus test systems.The problem formulation in this research is a nonlinear mixed integer which requires a complex optimization tool to solve the allocation problem. For this purpose, a new algorithm called Bees algorithm is proposed to optimally allocate the devices in the system effectively in order to achieve the objective function.

2 Optimal FACTS Allocation

2.1 Problem Formulation

The RPF with FACTS devices is used to evaluate the feasible ATC value of power transactions. The objective function is to maximize the power that can be transferred from a specific set of generators in a source area to loads in a sink area subject to voltage limits, line flow limits and FACTS devices operation limits.

Four types of FACTS devices are included; Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Shift Transformer (TCPST), Static Var Compensator (SVC) and Unified Power Flow Controller (UPFC). The mathematical models of the FACTS Devices are used to perform the steady state studies. Hence, TCSC is modeled to modify the reactance of the transmission lines directly. The TCPST varies the phase angle between the two terminal voltages, The SVC can be used to control the reactive compensation of a system at nominal voltage of 1 pu while the UPFC is the most versatile and powerful FACTS devices. The line impedance, voltages angle and the terminal voltages can controlled by it as well. The objective function is formulated as [3];

$$Max\ F(x) = P_{Di} \tag{1}$$

Subject to:

$$P_{Gi} - P_{Di} + \sum_{k=1}^{m(i)} P_{Pi}(\alpha_{Pk}) + \sum_{k=1}^{n(i)} P_{Ui(V_{Uk},\alpha_{Uk})} - \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S)\cos\left(\theta_{ij}(X_S) - \delta_i + \delta_j\right) = 0 \tag{2}$$

$$Q_{Gi} - Q_{Di} + \sum_{k=1}^{m(i)} Q_{Pi}(\alpha_{Pk}) + \sum_{k=1}^{n(i)} Q_{Ui(V_{Uk},\alpha_{Uk})} + Q_{Vi} + \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S)\sin\left(\theta_{ij}(X_S) - \delta_i + \delta_j\right) = 0 \tag{3}$$

$$P_{Gi}^{min} \le P_{G}i \le P_{G}i^{max} \tag{4}$$
$$Q_{Gi}^{min} \le Q_{G}i \le Q_{G}i^{max} \tag{5}$$
$$V_i^{min} \le V_i \le V_i^{max} \tag{6}$$
$$S_j \le S_{j\,max} \tag{7}$$
$$X_{Si}^{min} \le X_{Si} \le X_{Si}^{max} \tag{8}$$
$$Q_{Vi}^{min} \le Q_{Vi} \le Q_{Vi}^{max} \tag{9}$$
$$\alpha_{Pi}^{min} \le \alpha_{Pi} \le \alpha_{Pi}^{max} \tag{10}$$
$$0 \le V_{Ui} \le V_{Ui}^{max} \tag{11}$$
$$-\pi \le \alpha_{Ui} \le \pi \tag{12}$$

where,

F : total load in sink area

P_{Gi}, Q_{Gi} : real and reactive power generation at bus i

P_{Di}, Q_{Di} : real and reactive loads at bus i

$P_{Pi}(\alpha_{Pk}), Q_{Pi}(\alpha_{Pk})$: injected real and reactive powers of TCPST at bus i.

$P_{Ui(V_{Uk},\alpha_{Uk})}, Q_{Ui(V_{Uk},\alpha_{Uk})}$: injected real and reactive power of UPFC at bus i

V_i^{min}, V_i^{max}: lower and upper limit of voltage magnitude at bus i

S_i^{min} S_i^{max} : thermal limit of line i

Q_{Vi} : reactive power injected by SVC

V_i, V_j : voltage magnitude at bus i and bus j

$Y_{ij}(X_S), \theta_{ij}(X_S)$: magnitude and angle of the ij[th] element in bus admittance matrix with TCSC.

δ_i, δ_j : voltage angle of bus i and bus j

α_{Pi} : phase shift angle of TCPST at bus i

V_{Ui} : voltage magnitude of UPFC at bus i

α_{Ui} : voltage angle of UPFC at bus i

N : total number of buses

For calculating Total Transfer Capability (TTC) and ATC, the injected P_{Gi} at source area, and P_{Di} and Q_{Di} at sink area are increased in function of λ in which;

$$P_{Gi} = P_{Gi}^{\ 0}(1+\lambda K_{Gi}) \tag{13}$$
$$P_{Di} = P_{Di}^{\ 0}(1+\lambda K_{Di}) \tag{14}$$
$$Q_{Di} = Q_{Di}^{\ 0}(1+\lambda K_{Di}) \tag{15}$$

where P^o_{Gi}, P^o_{Di}, Q^o_{Di} are the base case injection at bus i and K_{Gi}, K_{Di} are the constant used to specify the rate of changes in load as λ varies. In order to maintain a zero balance, the incremental power losses resulting from increases in transfer power are allocated by a given formula. At PV buses, the reactive power is maintain at the base case value. However, in sink area, the reactive power demand (Q_{Di}) is incremented accordingly to real power in order to keep a constant value of power factor.

The rate of λ change from λ=0 corresponds to no transfer (base case) to λ=λmax corresponds to the largest value of transfer power that causes no limit violations. $P_{Di}(\lambda_{max})$ is the sum of load in sink area when λ=λmax while P^o_{Di} refers to the sum of load when λ=0. Therefore the sum of real power loads in sink area at the maximum power transaction in (normal or contingency case) represents the TTC value and ATC equals to *TTC*-base case value.

$$TTC = \sum_{i=1}^{ND\_SNK} P_{Di}(\lambda_{\max}) - \sum_{i=1}^{ND\_SNK} P_{Di}^{0} \tag{16}$$

2.2 Steady State Model of FACTS Devices

Different types of FACTS have been used in this study namely; TCSC, SVC, TCPST and UPFC. The line reactance can be changed by TCSC. SVC can be used to control the reactive compensation while TCPST varies the phase angle between the two terminal voltages. The UPFC is the most powerful and versatile FACTS. It may change the line impedance, terminal voltages and the voltage angle simultaneously.

In this paper the steady state model of FACTS devices are developed for power flow studies. The models are implemented using MATPOWER 3.2 [4]. The TCSC is a series connected device. It is modeled simply to modify the reactance of transmission line. It may be inductive or capacitive, respectively to decrease or increase the reactance of the transmission line. The reactance of TCSC is adjusted directly based on the reactance of the transmission line. The working range of

TCSC is between $-0.7X_L$ and $0.2\ X_L$ where X_L is the line reactance.

The SVC is a shunt connected static var generator or absorber. The SVC can be used to control the reactive compensation of a system at nominal voltage of 1 pu. In this study, it is modeled as an ideal reactive power injection at *bus i*, at where it is connected. The working range of SVC is between -100Mvar and 100MVar.

TCPST is a shunt-series connected device. The voltage angle between the sending and receiving end of transmission line can be regulated by TCPST. The working range of TCPST is between -5^o and 5^o. The steady state of UPFC in this paper is modeled with combination of TCSC and SVC.

2.3 Dependant and Control Variables

The objective function in the problem formulation dependent on the vector dependant variables which represent the typical load flow equations and a set of the control variables represents the operating limit of FACTS devices and security limits. The particular limit for each FACTS type is mentioned in the previous section. Besides, the considered two security limits are; the line thermal limits and bus voltage limits

3 Proposed Methodology

3.1 Overview of the Bees Algorithm

Bees Algorithm is a novel optimization method developed by D.T.Pham in 2006 [5,6] It is a kind of Swarm-based optimisation algorithms (SOAs) that mimic nature's methods to drive the search towards the optimal solution. This algorithm is inspired by honey bees' foraging behavior. In nature, bees are well known as social insects with well organized colonies. Their behaviors such as foraging, mating and nest site location have been used by researchers to solve many difficult combinatorial optimization and functional optimization problems. The Bees Algorithm has proved to give a more robust performance than other intelligent optimization methods for a range of complex problems.

3.2Natural World of Bees

A colony of honey bees can fly on itself in multiple directions simultaneously to exploit a large number of food sources. In principle, flower patches with plentiful amounts of nectar or pollen that can be collected with less effort should be visited by more bees, whereas patches with less nectar or pollen should receive fewer bees [5].

In a colony, the foraging process starts by sending out scout bees to search for potential flower patches. The scout bees move from one patch to another randomly. During the harvesting season, a colony continues its exploration, keeping a percentage of the population as scout bees [5]. Those scout bees that found a patch deposit their nectar or pollen when they return to the hive and go to the "dance floor" to perform a dance called as the "waggle dance" [6].

This dance contains three pieces of information regarding a flower patch: its distance from the hive, the direction in which it will be found, and its quality rating (or fitness) [5]. This dance is necessary for colony communication, and the information helps the colony to send its bees to flower patches precisely, without using guides or maps.

The information provides from the dance enables the colony to evaluate the relative merit of different patches according to both the quality of the food they provide and the amount of energy needed to harvest it.

The dancer (scout bees) goes back to the flower patch with follower bees that were waiting inside the hive, after the waggle dance. More follower bees are sent to more promising patches. This allows the colony to gather food in fast and efficiently. The bees monitor its food level during harvesting from a patch to decide upon the next waggle dance when they return to the hive. More bees will be recruited to that source if the patch is still good enough as a food source. This information will be advertised in the waggle dance.

3.3 Description of Bees Algorithm

This section summarizes the main steps in BA to optimally allocate the FACTS devices to enhance ATC. The flowchart of the algorithm is shown in its simplest form in Figure 1. This flowchart represents the foraging behavior of honey bee for food.

This algorithm requires a number of parameters to be set, namely, number of scout bees (*n*), number of sites selected for neighbourhood search (out of *n* visited sites) (*m*), number of top-rated (elite) sites among *m* selected sites (*e*), number of bees recruited for the best *e* sites (*nep*), number of bees recruited for the other (*m*-*e*) selected sites (*nsp*), and the stopping criterion.

Step 1: The algorithm start with initial population of n scout bees. The initial population is generated from the following parameters [7];

n_{FACTS} : the number of FACTS devices to be simulated

n_{type} : FACTS types

$n_{Location}$: the possible location for FACTS devices

$n_{individual}$: the number of individual in a population.

The number of individual in a population is calculated using the following equations, where:

$n_{individual} = 3 \times n_{FACTS} \times n_{Location}$

Step 2: the fitness computation process is carried out for each site visited by a bee by calculating the ATC.

Step 3: repeat (*step 4-8*) until stopping criteria is not met. *Else* terminate.

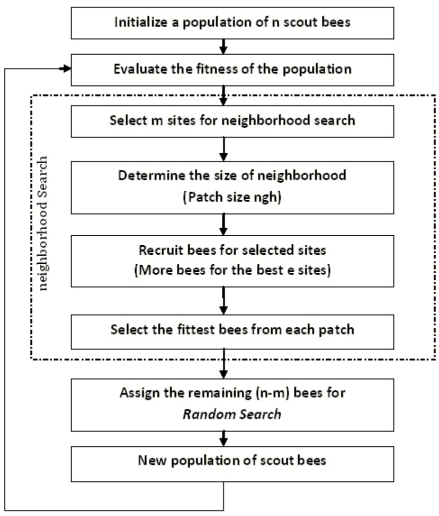

Figure 1: Flowchart of Bees Algorithm

Step 4: bees that have the highest fitnesses are chosen as "selected bees" (*m sites*) and sites visited by them are chosen for neighbourhood search.

Step 5: It is required to determine the size of neighborhood search done by the bees in the "selected sites".

Step 6 and 7: the algorithm conducts searches around the selected sites based on size determined in the step 4. More bees are assigned to search in the vicinity of the best e sites. Selection of the best sites can be made directly according to the fitnesses related to them. In other word, the fitness values are used to determine the probability of the sites being selected. Searches in the neighbourhood of the best e sites which represent the most promising solutions are made more detailed by recruiting more bees for the best e sites than for the other selected sites [5]. Together with scouting, this differential recruitment is a key operation of the Bees Algorithm [5].

Step 8: The remaining bees (n-m) are sent for *random search* to find other potential sites.

Step 9: Randomly initialized a new population.

Step 10: Find the global best point.

3.4 Genetic Algorithm

A Genetic Algorithm (GA) is based on the mechanism of natural selection. It is a powerful numerical optimization algorithm to reach an approximate global maximum of a complex multivariable function over a wide search space. It always produces high quality solution because it is independent of the choice of initial configuration of population.

In GA, the solution to a problem is called a chromosome. A chromosome is made up of a collection of genes which are simply the parameters to be optimized. A genetic algorithm creates an initial population (a collection of chromosomes), evaluates this population, then evolves the population through multiple generations using the genetic operators such as selection, crossover and mutation in the search for a good solution for the problem at hand.

4 Case Studies

The solutions for optimal location of FACTS devices to maximize the ATC that can be transferred from a specific set of generators in a source area (Bus 69) to loads in a sink area (Bus 23) subject to voltage limits, line flow limits and FACTS devices operation limits for IEEE118 bus test system was obtained and discussed below. The simulations studies were carried out on Intel Quad Core Q6600 running at 2.4GHz system in Matlab 7 environment.

TABLE I
PARAMETERS SET FOR GA AND BA FOR
IEEE118 BUS SYSTEM

GA	*Population size*	2805
	Crossover rate, μ_c	0.6
	Mutation rate, μ_m	0.01
	Number of generation	100
BA	*Number of scout bees, n*	2805
	Number of sites selected for neighbourhood search, m	1964
	Number of best "elite" sites out of m selected sites, e	982
	Number of bees recruited for best e sites, nep	30
	Number of bees recruited for the other (m-e) selected sites, nsp	15
	Number of iterations, R	100

The system consists of 55 generators with 187 branches. The bus and line data can be found in reference [8]. Table I shows the GA and BA parameters used for simulation purposes. The system was tested under two FACTS devices installation scenarios: single type and multi-type of FACTS devices. For each case, a total of five FACTS devices were installed in order to enhance the transferred power from source area to sink area. The location, setting and type of FACTS devices are obtained using GA and BA techniques and it is given in Table II. The comparison shown in the Table has proved that BA can be competently used with fast convergence compared to GA for FACTS devices allocation problem in large scale system.

The ATC before installation of any FACTS devices is 534.91MW with the limit condition of bus 23 voltage. In the case of single type of devices, it has shown that TCSC, SVC, UPFC and TCPST can be used for ATC enhancement. However, compared to the percentage of ATC increment, UPFC shows the best performance using both techniques with 93.39% and 97.04% using GA and BA respectively. Next to UPFC, SVC gives ATC of 93.29% and 95.45% using GA and BA respectively. TCSC increases 57% and 57.29% using GA and BA respectively, while TCPST gives the lowest percentage of ATC increment. In this system, the bus voltage violation limit dominates and therefore FACTS devices are employed for reactive power and voltage control. In that case SVC and UPFC is the best choice of FACTS type. TCSC and TCPST are mainly used for active power control. Hence, in this system TCSC and TCPST are not the best selection of FACTS devices for ATC enhancement. Comparing the cost, SVC is best option. Even though UPFC shows good performance in improving ATC, it is very much costlier than SVC.

In the case of multi-type devices, both techniques have chosen the same combination of FACTS devices for ATC enhancement: SVC, UPFC and TCPST. However, the setting and the location of FACTS devices found by BA technique has higher value of ATC compared to that found by GA. Instead, the allocation using GA has lower FACTS devices installation cost

TABLE II
RESULTS FOR IEEE 118BUS SYSTEM

ATC without FACTS		Type	Allocation Technique	ATC with FACTS Devices					
ATC(MW)	Limit condition			Facts Type	Size (rated value)	Location	ATC (MW)	Percentage of Increment	Cost of Installations (US$Million/yr)
534.91	V_{23}	Single Type	GA	TCSC	-0.69% X_{line} -0.69% X_{line} -0.69% X_{line} -0.69% X_{line} -0.69% X_{line}	Line 23-25 Line 24-70 Line 19-20 Line 25-27 Line 20-21	839.83	57.00%	1.332
			BA	TCSC	-0.70% X_{line} -0.70% X_{line} -0.70% X_{line} -0.70% X_{line} -0.70% X_{line}	Line 23-25 Line 30-17 Line 24-70 Line 19-20 Line 25-27	841.41	57.29%	1.414
			GA	SVC	-99.98MVAR -90.86MVAR -97.86MVAR -63.76MVAR -95.08MVAR	Bus 96 Bus 30 Bus 38 Bus 37 Bus 23	1033.97	93.29%	1.241
			BA	SVC	-100MVAR -100MVAR -99.64MVAR -67.52MVAR -98.32MVAR	Bus 23 Bus 37 Bus 38 Bus 45 Bus 30	1045.52	95.45%	1.338
			GA	TCPST	-4.9 4.1 4.9 4.9 -4.9	Line 15-17 Line 69-70 Line 32-114 Line 26-25 Line 27-32	541.77	1.28%	1.487
			BA	TCPST	-4.4° 4.9° -4.9° 4.7° 4.9°	Line 31-32 Line 26-25 Line 27-32 Line 114-115 Line 32-114	541.93	1.31%	1.124
			GA	UPFC		Line 23-25 Line 38-65 Line 21-22 Line 22-23 Line 71-73	1034.48	93.39%	12.31
			BA	UPFC		Line 23-25 Line 38-65 Line 21-22 Line 22-23 Line 20-21	1054.02	97.04%	14.16
		Multi-type	GA	SVC UPFC TCPST	-99.9MVAR -4.04°	Bus 23 Line 30-38 Line 24-70 Line 22-23 Line 75-77	1245.42	132.82%	11.147
			BA	SVC UPFC TCPST	-98.7MVAR -4.9°	Bus 23 Line 30-38 Line 24-70 Line 21-22 Line 15-17	1247.75	133.26%	15.933

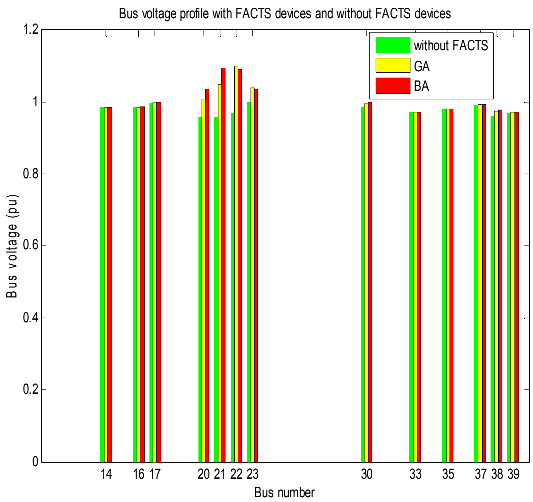

Figure 2: Voltage Profile

compared to BA. This is mainly due to the objective function of the allocation is to find the best allocation of FACTS devices in order to enhance ATC. Therefore, the allocation technique can only find the best allocation according to its objective function.

In all cases, it is observed that FACTS devices improve the power flow of the lines near to its thermal limits and at the same time improve the bus voltage profiles. It is concluded that for an IEEE118 bus system for single type scenarios, UPFC is the best choice of FACTS devices for ATC enhancement, but SVC is cost wise cheaper while considering better improvement in system loadability. For multi-type cases, increment of ATC is much better than single type case. However, compared to its installation cost and increment of ATC, single type case is much better. For all of the cases, BA always outperformed GA in term of objective function (ATC) and speed of convergence.

Figure 2 shows the improvement of bus voltage profile on selected bus when FACTS devices are installed in the system for ATC enhancement. It is observed that the voltage profile on buses which are connected to the bus where FACTS devices are installed has improved while BA is always shows better improvement on the voltage profile compared to GA.

5 Conclusion

This paper introduces a novel method to find the optimal location and parameter setting of FACTS devices for ATC enhancement for single type and multi-type FACTS devices using BA. Simulations were performed on large scale system: an IEEE118 bus test system. The results show the effectiveness of the new approach in simultaneously optimized the FACTS location, rated values and FACTS types. In the case of multi-type of FACTS devices, the type of devices to be placed is also considered as a parameter in the optimization. The algorithm generally outperformed the GA techniques that were compared with it in terms of speed of optimization and accuracy of the results obtained. The Bees algorithm converged to the maximum without becoming trapped at local optima. The main advantage of BA is that it does not require external parameters such as cross over rate and mutation rate etc, as in case of genetic algorithms these are hard to determine in prior. The other advantage is that the global search ability in the algorithm is implemented by introducing neighborhood source production mechanism which is a similar to mutation process. As far as the authors are concerned, this is the first application of bees algorithm in power system application regarding FACTS devices. Ideas presented in this paper can be applied to many other power system problems also

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