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Optimal Multi-type FACTS Allocations in Deregulated Electricity Market Using Bees Algorithm for Generation Cost Reduction

Abstract— This paper presents the application of Bees Algorithms (BA) technique to find the optimal number and location of Flexible AC Transmission System (FACTS) devices to achieve the power system economic generation in deregulated electricity market. Using the proposed method, the location, types, and ratings of FACTS devices are optimized simultaneously. Different kinds of FACTS devices, namely TCSC, SVC and TCPST, are tested in this study. While finding the optimal location, line thermal limits, voltage limits and FACTS operation limits are taken as constraints in the operation of the system. In order to demonstrate the effectiveness of the algorithm in reducing the overall system cost function, IEEE9 Bus and IEEE30-Reliability Test system are used. A Genetic Algorithm (GA) technique is used for validation purposes. The simulation results validate the capability of this new approach in minimizing the overall system cost function, which comprises of the investments costs of FACTS devices and generation cost and are encouraging for further improvements for application in deregulated electricity market.

Keywords – FACTS Allocation, Optimal Power Flow, Bees Algorithm, TCSC, SVC, TCPST.

I. INTRODUCTION

The implementation of FACTS devices in power system has been growing since the Electric Power Research Institute (EPRI) has introduced this technology in 1980s. In reality, several difficulties in the power system operation can be overcome by selecting the appropriate FACTS devices as they offer, to some extents, a degree of freedom over the influence of the system parameters such as series and shunt impedances, current and voltages [1].

The performance of the FACTS devices extends the possibility that current through a line can be controlled at a reasonable cost, enabling large potential of increasing the capacity of existing lines, and use of one of the FACTS devices to enable corresponding power to flow through such lines under normal and contingency conditions. Several studies [2]-[4] have found that FACTS technology not only provides feasible and practical solutions for increasing trend in transmission system capacity but also increases Available Transfer Capability (ATC), relieves congestion, improves reliability and enhances system operation and control**.**

These reveals that FACTS devices can be placed in the power systems for different reasons and their suitable locations can be determined by applying various systematic methods. For instance, FACTS devices can be used to reduce the flow on the overloaded line and to increase the use of alternative paths to excess capacity. This allows for increased transfer capability in existing transmission line much closer to their thermal limits. However, the installation of particular FACTS devices at a location of interest in the system is restricted by its high cost. Therefore, the problem of finding out which positions are the most effective and how many devices have to be installed on economic basis is a question of great significance by many power system researchers.

The main objective of this paper is to develop an algorithm to allocate the compensation devices at a strategic location in power network. The objective function is to minimize the total production cost which includes the generation cost and the investment cost of FACTS devices. In achieving the objective, the control of all devices in the system should be in good coordination since it affects one another. However, in reality, it is not an easy task to bring the control of all devices to work together. Thus, the existence of the Optimal Power Flow (OPF) software tool is a necessary. The existing traditional OPF is extended to include the representations of FACTS devices.

This paper is divided into several sections. Section II presents the literature survey on allocation of FACTS devices in minimizing the cost function of the system. Section III illustrates the mathematical model of the FACTS Devices. Section IV describes the cost function while Section V details out the Bees algorithm for OPF incorporating FACTS controllers. The simulation results are presented and discussed briefly in Section VI. Section VII concludes the paper.

II. LITERATURE SURVEY

Several recent studies had concentrated on placing different FACTS devices optimally in the power networks considering the economic aspect and dispatch as their objective functions. For instance, L.J.Cai et al [5] studied the optimal location of FACTS considering the generation cost of the power plant and investment cost of the devices. The

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allocation of FACTS was done using GA and no comparison has done using other technique.

In [6], Ippolito et al discussed optimal allocation of UPFC for maximizing system capabilities, social welfare and to satisfy contractual requirements in an open market power. The proposed methodology was based on genetic algorithms and able to identify the optimal number of FACTS in an assigned power system network. Yet, this paper, only concentrated on UPFC. Ayman et al [7] studied the placement of FACTS in power network considering generation cost minimization which includes the active and reactive power using Low Discrepancy Sequences. One of the drawbacks of this algorithm is the selection of the number of points in the search space domain for each iterations is a time consuming one, especially when the number of the optimization variables is high and the system is complex. Thus, this paper overcomes the abovementioned drawbacks by splitting the points and such the computational time can be reduced significantly. However the proposed algorithm required longer computational time for large power systems.

H.Farahmand et al [8] focused on the study of the best location for SVC to improve voltage profile as well as maximize the available transfer capability in order to achieve lower prices. However, only capital cost of SVC was considered and no generation cost for FACTS allocation purposes. Furthermore, this research only considered one type of FACTS. In [9], S.N.Singh et al suggested few optimal locations of FACTS devices and then determined the best optimal location in order to reduce the production cost along with the device cost. The nonlinear optimization problem was solved based on the sensitivity of the real power flow performance index. However, this method is a time consuming algorithm since the reactance value of TCSC was tested randomly for every line. Moreover, this paper did not show any details regarding the generation cost and the resulting savings. Additionally, in the case of TCPAR, the FACTS devices cost was not considered.

K.Vijayakumar et al, in [10] presented a novel method based on Genetic Algorithm for optimal locations of FACTS controllers in multi-machine. The proposed algorithm optimized simultaneously the rated values, location and types of FACTS devices in order to minimized the overall system cost which comprises of FACTS investments cost and generation cost. However, only two types of FACTS was considered; TCSC and UPFC. Besides, this paper also did not show any details regarding the generation cost and the resulting savings offered by the FACTS devices.

The introduction of FACTS in a power system improves the stability, reduces the losses and the cost of generation and also improves the system loadability. These were proved by J.Baskaran et al in [11]. In this paper, the optimal location of FACTS devices was chosen based on the economic saving function, which obtained by energy loss reduction. However, the simulations were done for single types of FACTS devices. Even though, the results highlighted the percentage of total reduction in power losses, but they did not specifically show the best location for the installations of FACTS devices to achieve these results.

In [12], M.Saravanan et al attempted to find the optimal location of FACTS devices for getting maximum system loadability and minimum cost of installation of FACTS devices for single and multi-type of FACTS devices using Particle Swarm Optimization. The results showed that UPFC gives maximum loadability at higher installation cost, while TCSC required minimum cost of installation with better improvement in system loadability. SVC, on the other hand gave lowest cost of installation but with minimum improvement in system loadability. As to be presented later, we have also discovered the optimal number of FACTS devices needed to be installed in the system for certain system loadability.

A.A.Alabduljabbar demonstrated in [13], that the optimal allocation of SVCs was a cost effective measure since the installed SVCs reduce the overall generation costs and additionally contributed to enhance system security of the transmission network by improving the damping of electromechanical oscillations. The studies were carried out using OPF and GA to ensure techno-economic solution for the network in steady state. Nevertheless, only one type of SVC was considered ~~in~~ which hinder the comparison against other types of FACTS devices in reducing the system cost functions.

The effects of level of TCSC compensation on spot price power market was raised by G.B.Shrestha et al in [14]. OPF incorporating TCSC was used to demonstrate the influence of TCSC in the loads and generation at different buses to achieve significant increase in social benefits. However, the best location to install TCSC was made based on the trial and error method. This method might not promise for a good solution and took some time to produce a better solution.

Variable Series Capacitor (VSC) and TCPST are two types of FACTS devices used by T.T.Lie et in [15] to reduce the total cost of operating and to avoid the problem of load curtailment. A two level algorithm, the decomposition-coordination was used. In the first level, a trial value of the FACTS devices compensation was decided. In the second level, a conventional OPF problem was solved. However one of the drawbacks of this method is to decide the compensation value of the FACTS devices, in which is based on trial and error. This method might not yield good solution and takes longer time to determine the appropriate compensation value of the FACTS devices.

The extensive survey of the existing works reveals that the optimal FACTS solution problem is one of main aspects in the enhancement of transmission system. However, the installation of particular FACTS devices at a location of interest in the system is restricted by its high cost. Therefore, adverse interaction between FACTS devices and the issue of where these devices should be placed on economic basis have received great attention by many researchers. Both these issues are addressed in this paper and a new optimization algorithm is proposed and compared to the existing established method.

III. FACTS MODEL

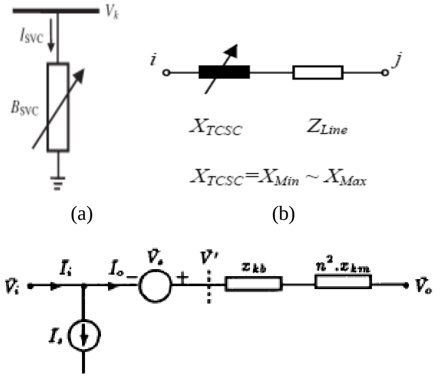
A. FACTS Devices Selection

The active power, P_{ij} and reactive power, Q_{ij} flow through the transmission line *i-j* is a function of voltage magnitude *Vi, Vj*, line impedance *Xij* and phase angle between the sending and receiving end voltages, *δi-δj*. The selection of FACTS devices in this study is based on these power equations.

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \quad (1)$$

$$Q_{ij} = \frac{V_i}{X_{ij}}[V_i \quad V_j cos(\delta_i \quad \delta_j)] \quad (2)$$

It can be seen clearly from the equations, V,δ and X should be controlled either individually or simultaneously in order to control the power flow of the line. Thus FACTS devices can be applied to control the power flow by changing those parameters so that the power flow can be optimized. Different types of FACTS have been used in this study namely; Static VAR Compensator (SVC) and Thyristor Control Series Compensator (TCSC) and Thyristor Phase Shift Transformer (TCPST). The block diagrams of the devices are shown in Figure 1.



(a) (b)

(c)

Figure 1: Block diagram of the (a) SVC (b) TCSC (c) TCPST

As shown in Figure 1, 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.

B. Mathematical Model of FACTS Devices

1) SVC

The SVC is a shunt connected static VAR generator or absorber. The SVC can be used to control the reactive compensation of a system. B_{SVC} represents the controllable susceptance of SVC. It can be operated either as inductive or capacitive compensator. 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 -100 MVAR and 100 MVAR [5].

2) TCSC

The TCSC can change the line reactance so as to function as inductive or capacitive compensation .The reactance of TCSC is adjusted directly based on the reactance of the transmission line.

$$X_{ij} = X_{line} + X_{TCSC}, \quad X_{TCSC} = r_{TCSC} \cdot X_{line} \quad (3)$$

Where X_{line} is the reactance of the transmission line, X_{TCSC} represents the reactance contribute by TCSC and r_{TCSC} represents the degree of compensation of TCSC. The working range of TCSC ($X_{MIN} \sim X_{MAX}$) is set between -0.7 X_{line} and 0.2 X_{line} [5].

3) TCPST

TCPST is a shunt-series connected device. It consists of three non-identical transformers winding with a switch arrangement that can bypass a winding or reverse its polarity. This device allows increasing or decreasing the electrical voltage phase angle of the circuit by addition of a quadrature component to the prevailing bus voltage. This means 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° to +5°. The phase shifting introduced by TCPST should not be too high since it may affect the voltage amplitude as well.

IV. PROBLEM FORMULATION

The main objectives of this work is to determine the optimal choice of location and the optimal parameter setting of the FACTS device in the power network in order to minimize social welfare or the total cost of the system which comprises the generation and FACTS investments costs. In this work, a modified version of power simulation package MATPOWER 3.2 [16] is used. An OPF incorporating the FACTS devices mathematical model and investment costs are implemented in order to study the system.

A. Generation cost

The generating cost function has been approximated as a quadratic polynomial function in $/hr given by:

$$f_1(P) = aP^2 + bP + c \quad (4)$$

Where P is the generators output in MW and a, b and c are the generating coefficients in $\$/MW^2hr$, $/MWhr and $/hr respectively.

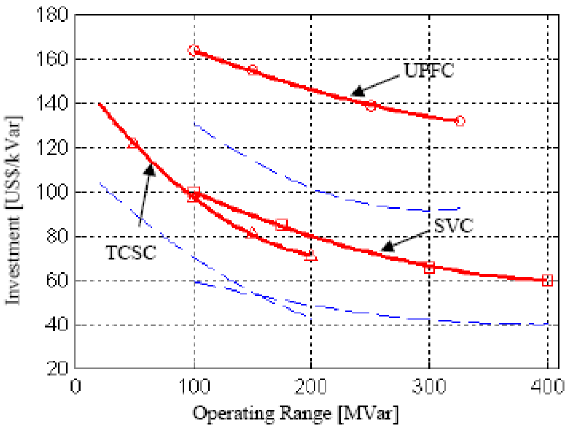


Figure 2: Cost function of FACTS devices.

_______: upper limit: total investment cost
_ _ _ _ _ : lower limit : equipment cost

B. FACTS Devices Cost Functions

It is important to take into account the economical aspects of the FACTS devices presence in the power system due to its high investment and operating cost. Hence, based on the Siemens AG Database [17] the cost function for SVC and TCSC are as follows:

$$f_{SVC} = 0.0003s^2 - 0.3051s + 127.38 \text{ (US\$/KVAR)} \quad (5)$$

$$f_{TCSC} = 0.0015s^2 - 0.7130s + 153.75 \text{ (US\$/KVAR)} \quad (6)$$

Where f_{SVC} and f_{TCSC} are in US $/KVAR and s is the operating range of FACTS devices in MVAR. The cost function for SVC and TCSC is shown in Figure 2. The cost of TCPST is normally fixed and based on the rating of the circuit in which they are installed. In this study, the cost is fixed at $100/KVA.

C. Optimal Power Flow with FACTS Controllers

As mentioned previously, the objective function is to minimize the overall total cost of the system which includes the generation and investment cost of FACTS devices. This objective function is also known as social welfare. The optimal allocation of FACTS controller can be expressed as follows:

$$Min \quad F(x) = f_1(P) + f_2(g) \quad (7)$$

Subject to:

$$E(g,b) = 0 \quad (8)$$

$$M_1(g) < m_1, M_2(b) < m_2 \quad (9)$$

Where,

F(x) : the overall total cost function which includes the investment cost of FACTS $f_2(g)$ in US$/yr and generation cost, $f_1(P)$ in US$/hr

$E(g,b)$: conventional power flow equation

g : the variables of FACTS devices

b : operating state of the power system

P : active power outputs of generators

$M_1(g)$: inequality constraints for FACTS controller

$M_2(b)$: inequality constraints for conventional power flow.

Since the cost function of generators outputs is in US$/hr, the total cost of FACTS devices is converted to the same units. Normally, the life expectancy of FACTS devices is assumed to be ten years. This value has been applied only to unify the units and has no influence in global optimization. Therefore, the average value of investment cost is calculated as follows.

$$f_2(g) = \frac{f_2(g)}{8760 \times 10} \quad \text{(US\$/hr)} \quad (10)$$

As mentioned previously, the variation of FACTS location, parameters and types influences the objective function. It is not an easy task to find optimal location, types and parameters for FACTS simultaneously using conventional optimization methods. Therefore there is a need to determine better optimization method in order to achieve the objective function. In this study, Bees Algorithms is employed for the mentioned purposes. Bees Algorithms is a new term in optimization world. The Bees Algorithm [18] is a population-based search algorithm first developed in 2006. It mimics the food foraging behavior of swarms of honey bees. In its basic version, the algorithm performs a kind of neighborhood search combined with global search and can be used for both combinatorial optimization and functional optimization.

V. PROPOSED METHODOLOGY

A. Overview of the Bees Algorithm

Bees Algorithm is a novel optimization method developed by D.T. Pham in 2006 [18, 19] It is a kind of Swarm-based optimization 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.

B. Natural 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 [18].

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 [18]. 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" [18].

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) [19]. 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.

C. Description of Bees Algorithm

This section summarizes the main steps in BA to optimally allocate the FACTS devices to minimize the overall total cost. The flowchart of the algorithm is shown in its simplest form in Figure 3. 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;

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:

$$n_{individual} = 10 \text{ x } n_{FACTS} \text{ x } n_{Location}$$

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

Step 3: repeat (*step 4-8*) until stopping criteria is not met. The stopping criteria in this study is set to $R = 25 \text{ x } n_{FACTS}$. (*Else* terminate.)

Step 4: bees that have the highest fitness's are chosen as "selected bees" (*m sites*) and sites visited by them are chosen for neighborhood search. Best patches are set to be 20% of the population size.

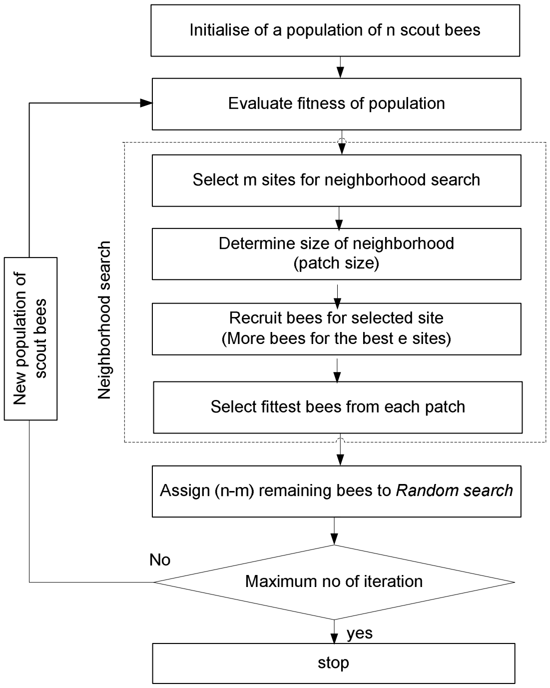


Figure 3: Flowchart of Bees Algorithm

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. In this case, the number of bees for elite site is set to be 30. Selection of the best sites can be made directly according to the fitness's 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 [18]. Together with scouting, this differential recruitment is a key operation of the Bees Algorithm [18].

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.

D. Description of Used 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. Many researches [20-22] suggested that, the implementation of GA is quite easy and the computational is relatively simple. However, it can be noticed that GA has possibility to converge prematurely to a suboptimal solution.

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.

In order to optimally allocate the FACTS devices, the parameters used for GA is summarized in Table I. In the proposed GA, method of tournament selection is used for selection [21]. This method chooses each parent by choosing n_t (tournament size) players randomly. In this paper the chosen size is 2. Then uniform crossover type is selected with crossover rate of 0.8 while the mutation rate is chosen to be 0.01 with uniform type. A MATPOWER 3.2[16] is used to solve the power flow calculation in order to calculate the cost function.

VI. CASE STUDIES AND RESULTS

A. IEEE9Bus-RTS

The network shown in Figure 4, used in this study, is the IEEE9 Bus- Reliability Test system which consists of 9 lines and 3 generators. The network data are available in [16]. The voltage limits are set to be between 0.95pu and 1.15pu. To verify the validity of the results of the proposed algorithm, a Genetic Algorithm method is programmed and used as benchmark. Table I shows the GA and BA parameters used for simulation purposes. Simulation studies were done for different scenarios in the IEEE 9Bus -RTS.

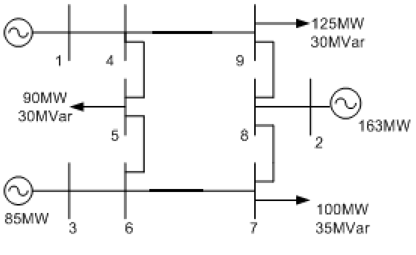


Figure 4: Diagram of IEEE9 Bus -RTS

Six scenarios are considered:

- twice normal loading at bus 5
- three times normal loading at bus 5
- twice normal loading at bus 9
- three times normal loading at bus 9
- three times loading at bus 5 and without generation at bus 3
- twice normal loading at bus 9 and without generation at bus 2

For each case, the simulations are done without installation of FACTS devices and with FACTS devices. For every particular cases mentioned above, simulations are done with installation of only one FACTS device at a time, then the system is tested with installation of multi-type of FACTS devices.

The complete results for the cases tested with IEEE9 bus system are shown in Table II. Only the best results for the particular cases are shown in this table, where at some time, the installation of single FACTS device in the system could alleviate the power flow problem in the system. However, in comparison with the FACTS costs and its total benefit for the overall generation cost, FACTS device will not lead to a cost reduction in the particular situation. For most of the time TCSC produces those results. This may be because of the higher investment cost of TCSC when compared to SVC. Therefore, most of the time, SVC is chosen as the best

TABLE I

PARAMETERS SET FOR GA AND BA FOR 9 BUS SYSTEM

GA	*Population size*	$135n_f$
	Crossover rate, μ_c	0.8
	Mutation rate, μ_m	0.01
	Number of generation	100
BA	*Number of scout bees, n*	$90\ n_f$
	Number of sites selected for neighbourhood search, m	0.2n
	Number of best "elite" sites out of m selected sites, e	m/2
	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	$25\ n_f$

- n_f: Number of FACTS

TABLE II

RESULTS FOR IEEE 9 BUS SYSTEM

Scenario	Bus	Total cost without FACTS (US$/hr)	Allocation Technique	Device type	Rating of devices	Location	Total cost with FACT (US$/hr)	Saving (US$ Million/yr)
Twice normal loading	5	7889.07	GA	SVC	-22.96MVAR	Bus 5	7884.28	0.0420
				SVC **SVC**	**-20.72 MVAR** **-9.26MVAR**	**Bus 5** **Bus 9**	**7883.05**	**0.0530**
			BA	SVC	-19.94MVAR	Bus 5	7884.16	0.0430
				SVC **SVC** **SVC**	**-1.44MVAR** **-17.42MVAR** **-11.86MVAR**	**Bus 7** **Bus 5** **Bus 9**	**7883.0**	**0.0531**
3 Times normal loading	5	11237.91	GA	SVC	-53.18 MVAR	Bus 5	11193.22	0.3910
				SVC **SVC**	**-5.81MVAR** **-15.18MVAR**	**Bus 5** **Bus 9**	**11188.47**	**0.4330**
			BA	SVC	-56.72MVAR	Bus 5	11193.03	0.3931
				SVC **SVC** **SVC**	**-3.3MVAR** **-53.74MVAR** **-21.14MVAR**	**Bus 6** **Bus 5** **Bus 9**	**11187.85**	**0.4385**
3 times normal loading and without generation at bus 3	5	14768.94	GA	**SVC** **SVC** **TCPST**	**-27.58MVAR** **-17.98MVAR** **-5^{o}**	**Bus 9** **Bus 5** **Line 3 –Line 6**	**14367.9**	**3.5130**
			BA	**SVC** **SVC**	**-30.8MVAR** **-17.78MVAR**	**Bus 5** **Bus 9**	**14350.8**	**3.663**
Twice normal loading	9	9089.82	GA	SVC	-37.14MVAR	Bus 9	9071.72	0.1580
				SVC **SVC**	**-38.5MVAR** **-8.5MVAR**	**Bus 9** **Bus 8**	**9070.86**	**0.1661**
			BA	SVC	-40.26MVAR	Bus 9	9071.61	0.1595
				SVC **SVC** **SVC**	**-11.04MVAR** **-6.16MVAR** **-41.68MVAR**	**Bus 8** **Bus 7** **Bus 9**	**9070.53**	**0.1689**
3 Times normal loading	9	14628.89	GA	TCSC	$-8.5\%X_{line}$	Line 1-Line 4	14565.89	0.5510
				SVC	-100MVAR	Bus 9	14262.95	3.2050
				TCPST	3.624^{o}	Line 4-Line 5	14451.09	1.550
				SVC **SVC** **SVC**	**-31.28MVAR** **-14.68MVAR** **-100MVAR**	**Bus 8** **Bus 5** **Bus 9**	**14248.01**	**3.3360**
			BA	TCSC	$99.68X_{line}$	Line 5- Line 6	14430.83	0.5520
				SVC	-100MVAR	Bus 9	14262.95	3.2056
				TCPST	4.99^{o}	Line 4- Line 5	14447.41	1.5890
				SVC **SVC** **SVC**	**-39.84MVAR** **-22.98MVAR** **-99.4MVAR**	**Bus 4** **Bus 8** **Bus 9**	**14246.29**	**3.3515**
2 times normal loading and without generation at bus 2	9	13592.66	GA	**SVC** **SVC**	**71.64MVAR** **91.9MVAR**	**Bus 8** **Bus 7**	**12824.20**	6.731
			BA	**SVC** **SVC** **SVC**	**90.64MVAR** **98.01MVAR** **94.14MVAR**	**Bus 4** **Bus 8** **Bus 9**	**12819.32**	6.773

FACTS device. The results with bold function in Table II represent the results of multi-type FACTS devices for the particular case. The effects of types, rated value and location of FACTS devices on system loadability and cost reduction are observed from Table II.

In the case of single type FACTS devices, it is observed that placing SVC is best compared to TCSC and TCPST. The results summarized in Table II reveal the feasibility of the proposed approach, achieving a substantial reduction of the overall production cost for the system. In particular, as shown in Table II, a significant reduction of total production cost in the network with FACTS devices installation can be highlighted in all cases, if compared with those of the network without FACTS devices. This is mainly due to the increased power transfer capability of the network with the FACTS devices installed. In network with FACTS, the power delivered by the costly generators represents lower portion of the total demand power compared with the power delivered by the same generators in the network without FACTS. From this situation, reduction of total production cost can be derived for the network with FACTS devices installed. The results presented in Table II, show a significant production cost reduction from 7889.07 US$/hr to 7883.0 US$/hr using BA approach, while reduced to 7883.05 US$/hr using GA. This shows a total saving of about 0.0531 US$M/yr using BA while 0.0530 US$M/yr using GA. This case clearly shows that BA is faster than GA to reach about the same results of objective functions. GA takes 100 generation to converge for the optimum solution while BA only takes 25 iterations to converge. Therefore, BA could reach the optimum solution in a very reasonable time and faster than GA. In particular, it clear that with all population sizes considered, BA performs better than GA in terms of best value of objective function as well as speed of convergence.

B. IEEE30Bus-RTS

To establish the availability of the proposed method, simulations are carried out on the modified IEEE30 Bus-RTS. The considered power system comprises six generators, 41 lines and 20 loads. The network data are available in [16]. The voltage limits are set to be between 0.9pu to 1.1pu. During the optimizations, network constraints which are voltages, thermal limits and FACTS devices operating limits are taken into consideration.

In order to reduce the overall generations cost, the FACTS devices were optimally placed in the network according to the following procedures:

1. The AC optimal power flow (OPF) was run repeatedly with a gradual increase in the network loading factor until it did not converge. The non-convergence was caused by the violation of one or more constraints in the network. The loading factor at the point of non-convergence was just above 1.735 for both active and reactive power. Hence, 1.735 loading factor was considered to be the limiting network loading and was used as a base case for FACTS devices placement. The generation cost for this network loading level was $F(x)_{orig}$ = 1221.63 $/hr. As mention previously, the MATPOWER toolbox was used, which contains the required ACOPF routines to calculate the cost function. The changing of the load level was achieved by multiplying all of the loads in the network by factor 1.735. This step will make sure all of the loads are changed at the same time. Table III shows data of load at the base case and after the increment of factor 1.735.

TABLE III

LOAD DATA AT BASE CASE AND AFTER INCREMENT

Bus	Base Case		With factor of 1.735	
	P (MW)	Q(MVAR)	P (MW)	Q(MVAR)
2	21.7	12.7	37.65	22.03
3	2.4	1.2	4.16	2.08
4	7.6	1.6	13.19	2.78
7	22.8	10.9	39.56	18.91
8	30	30	52.05	52.05
10	5.8	2	10.06	3.47
12	11.2	7.5	19.43	13.01
14	6.2	1.6	10.76	2.78
15	8.2	2.5	14.23	4.34
16	3.5	1.8	6.07	3.12
17	9	5.8	15.62	10.06
18	3.2	0.9	5.55	1.56
19	9.5	3.4	16.48	5.90
20	2.2	0.7	3.82	1.21
21	17.5	11.2	30.36	19.43
23	3.2	1.6	5.55	2.78
24	8.7	6.7	15.09	11.62
26	3.5	2.3	6.07	3.99
29	2.4	0.9	4.16	1.56
30	10.6	1.9	18.39	3.30

TABLE IV

PARAMETERS SET FOR GA AND BA FOR 30BUS SYSTEM

GA	*Population size*	615n_f
	Crossover rate, μ_c	0.8
	Mutation rate, μ_m	0.01
	Number of generation	200
BA	*Number of scout bees, n*	410 n_f
	Number of sites selected for neighborhood search, m	0.2n
	Number of best "elite" sites out of m selected sites, e	m/2
	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	25 n_f

n_f : Number of FACTS

2. The simulations are conducted in four scenarios in order to show the effectiveness of each type of FACTS devices in reducing the overall system cost function. Each time a simulation is carried out, the total of eight single type of FACTS devices are used for optimal placement in the network. Then, the system is tested with installation of multi-type of FACTS devices. Four FACTS devices of each type, 12 in total, are used for the same purpose. In order to perform comparative studies, the BA is compared to GA to optimally allocate the FACTS devices in system. In FACTS allocation, two variables per device to be determine, location and rating SVCs, 25 buses were considered as possible locations (excluding 5 generator buses) and the allowed rating was between 100MVAR (capacitive) and -100MVAR (inductive). For TCSC and TCPST, all 41 lines are considered as possible location for

installation. As far as rating limits are concerned they are as follows: TCPST, phase shift range from -5^o to 5^o; TCSC, range of XTCSC variation from $-0.7X_L$ and $0.2X_{L.}$Table IV shows the parameter setting for BA and GA for simulation purposes.

3. In order to prevent placement of two FACTS devices at the same bus or branch, a penalty factor was introduced. The penalty factor increases the cost of placing second FACTS devices at the same location and discard from further consideration.
4. The calculation of objection function is presented in a section problem formulation. The objection function is to minimize the overall system cost function or in other word to maximize the social welfare.

Table V shows the results of the performed optimization for allocation of required number of single and multi-type FACTS devices using BA and GA. The location, setting of FACTS devices and the respective overall system cost function and saving are shown clearly in this table.

This comparative studies show that BA outperformed the GA in term of proposing lower value of objective function. For cases of single and multi-type of FACTS devices, BA always produce lower value of the overall system cost function, in which gives higher value of saving in a year. The results of single type of FACTS devices using TCSC and TCPST are not included in the Table. After the optimization using GA and BA, it is obvious that these FACTS type will maximize the system loadability. However, in comparisons with the FACTS costs and its total benefit for the overall system cost, TCSC and TCPST will not lead to a cost reduction in this situation.

In the case of single type of FACTS devices, SVC shows the best performance compared to TCSC and TCPST using GA and BA. These allocations techniques show that only seven out of eight SVCs required in minimizing the overall system cost function. Using GA, the new total cost in which comprises of generation cost and FACTS devices investment cost is 1168.60 US$/hr. So the total saving is approximately 0.465 million US$/yr. However, using BA the new total cost of the overall system shows a bit lower compared to GA. BA could find better location and setting of SVCs in which could minimized the system cost function to 1167.36 US$/hr. This gives a total saving of 0.4754 million US$/yr. The best locations and to install SVCs and their respective settings that found by BA are Bus 6 with 2.9MVAR, Bus 23 with 17.44MVAR, Bus 2 with 3.86MVAR, Bus 29 with 85.78MVAR, Bus 27 with 54.1, Bus 16 with -19.24MVAR and Bus 9 with -25.78. The overall saving in the system using SVCs indicates a successful investment in these devices. These findings support the results published in [7, 13] where it was shown that the installations of single type of FACTS devices resulted in a significant saving in the production cost. It was also clear from the simulations using both techniques that the most selected buses for installation

TABLE V
OPTIMAL PLACEMENT OF FACTS DEVICES IN THE IEEE30BUS TEST SYSTEM

Case	Allocation Technique	Type of Device Used	Location	Rating of devices	Total cost with FACT (US$/hr)	Saving (US$ Million/yr)
Single Type	GA	SVC	Bus 4	8.12	1168.60	0.4645
			Bus 28	-2.42		
			Bus 23	14.08		
			Bus 27	35.28		
			Bus 29	96.00		
			Bus 15	4.28		
			Bus 21	-21.48		
	BA	SVC	Bus 6	2.9	1167.36	0.4754
			Bus 2	3.86		
			Bus 23	17.44		
			Bus 27	54.1		
			Bus 29	85.78		
			Bus 16	-19.24		
			Bus 9	-25.78		
Multi-Type	GA	SVC	Bus 9	-40.38	1189.00	0.2858
			Bus 16	-16.52		
			Bus 12	7.82		
			Bus 4	-2.18		
			Bus 27	24.6		
			Bus 8	-12.32		
			Bus 29	78.38		
			Bus 24	6.86		
		TCSC	Line 6-8	$-0.02X_{line}$		
			Line 21-22	$0.02X_{line}$		
	BA	SVC	Bus 2	9.04	1172.7	0.4286
			Bus 27	28.84		
			Bus 29	98.14		
			Bus 6	0.8		
			Bus 14	-19.98		
			Bus 8	-6.94		
			Bus 24	-25.84		
		TCSC	Line 3-4	$-0.0003\ X_{line}$		
		TCPST	Line 16-17	3.838^o		
			Line 12-15	2.575^o		
			Line 23-24	3.126^o		

of SVCs are Bus 23, Bus 27 and Bus 29. This is due to the critical voltages of those buses during the load increment. The injection of reactive power to those buses may prevent the voltages from collapse.

In the case of multi-type devices, the values tabulated in Table V are the best combination with minimum cost, minimum number of FACTS devices required for the particular load increment. In this case, the results performed by BA always better than the GA. After the optimization using GA, eight SVCs and two TCSC are selected to minimized the system cost to 1189 US$/hr, in which propose a total saving of approximately 0.2858millionUS$/yr. This does not indicate a significant saving as proposed by the BA. The optimization using BA indicates the best combination of FACTS devices that are required to minimize the total system cost to 1172.7US$/hr are using seven SVCs, one TCSC and three TCPST. This reveals that BA suggests higher number of FACTS devices to be used for the cost minimization compared to the GA. However, the total saving recommended by BA is absolutely higher than the GA. The FACTS type and their respective location and setting implied by BA are SVCs at Bus 2 with 9.04MVAR, Bus 27 with 28.84MVAR, Bus 29 with 98.14MVAR, Bus 6 with 0.8MVAR, Bus 14 with -19.98MVAR, Bus 8 with -6.94MVAR and Bus 24 with -25.84MVAR. Three TCPSTs located at Line 16-17 with 3.838^o, Line 12-12 with 2.575^o and Line 23-24 with 3.126^o, while one TCSC is installed at Line 3-4 with -0.0003X_{line}.

In all cases, it is observed that FACTS devices improve the line flows even nearer to their thermal limits and improve the voltage profile. For IEEE30 bus system, SVC is the best choice of FACTS type for overall system cost minimization. SVC has a lower cost of installation compared to TCSC and TCPST. Even though TCSC and TCPST have also improved the system loadability and reduced the generation cost, but their installation cost are higher compared to SVC. This will lead to increase the total production cost of the system. Therefore, the best choice goes to SVC.

The effect of numbers of FACTS devices versus the fitness function can be seen clearly from Figure 5. This figure shows that the totals of seven FACTS devices are enough to reduce the overall system cost function. Further increase in the number of FACTS devices will not lead to any further minimization in the overall production cost.

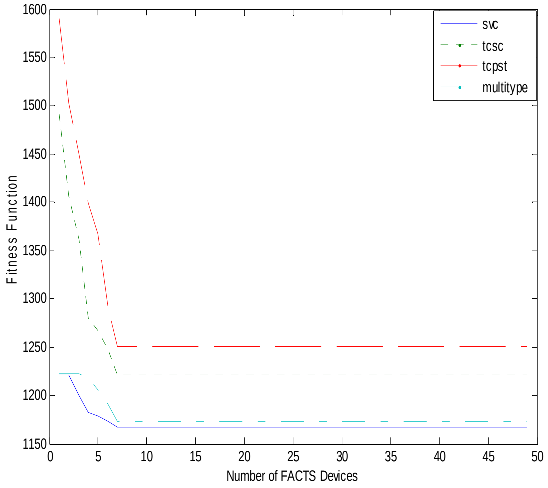


Figure 5: Effect of number of FACTS devices and fitness function

In term of speed of convergence, BA always converge faster than GA to a global better solution. To have a better clarity, the convergence characteristics in finding FACTS type, location and size of the selected FACTS devices is given in Figure 6 for BA and GA. This Figure shows that the convergence of BA is much better than the GA.

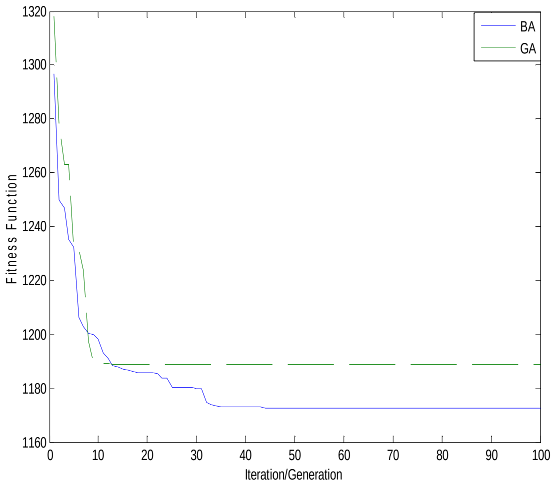


Figure 6: Convergence characteristics of BA and GA in finding solution for multi-type FACTS devices.

The computational time required to perform the optimization is mainly depends on the number of FACTS devices used and number of lines or buses in the system. In other word, it depends on the population size and number of iteration or generation. The best parameter setting for both techniques based on several tuning are shown in Table VI. The best elapsed time for GA for single type optimization is 5.12hrs while for BA is 4.17hrs. This shows that BA is faster than GA in term of computational time for the same case studies.

TABLE VI

COMPUTATIONAL TIME FOR BOTH TECHNIQUES

Allocation Technique	Computational time (second)	
	Single-type FACTS	Multi-type FACTS
BA	15033.00	23503.39
GA	18466.38	28245.74

VII. CONCLUSION

This paper has presented a new optimization algorithm to optimally allocate FACTS devices to minimize the total production cost. The simulation results have proven that the proposed algorithm has remarkable robustness in minimizing the overall system cost and maximizing system loadability. Furthermore, the results have also shown the effectiveness of the new approach in simultaneously optimized the FACTS location, rated values and FACTS types. It is a practical method for the allocation of FACTS devices in large power system.

The Bees algorithm converged to the maximum without becoming trapped at local optima. The algorithm generally outperformed the GA techniques that were compared with it in terms of speed of optimization and values of the results obtained. 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.

However, one of the drawbacks of the algorithm is the number of tunable parameters used. Nevertheless, it is possible to set the parameter values by conducting a small number of trials.

As far as the authors are concerned, this is the first application of Bees algorithm in power system application with regards to FACTS devices. Ideas presented in this paper can also be applied to many other power system problems. In near future the authors would like to report further related studies by including the generation and FACTS operational cost in the computation of ATC.

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