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Optimal Placement and Sizing of SVC for Loss Minimization and Voltage Profile Improvement using ABC Algorithm

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Abstract— **The placement of Flexible AC Transmission System (FACTS) devices in power system is of great significance to ensure the promising performance of the transmission network. The FACTS devices play an important role for power system security enhancement. The FACTS devices are used to regulate the active and reactive powers and to improve voltage profile, due to their robust, fast and flexible control characteristics. Due to their high capital cost, it is necessary to place these controllers optimally in a power system. Optimal placement of FACTS devices can control the line flows and can maintain the voltages at the desired level and so can improve the voltage stability. This paper presents Artificial Bee Colony (ABC) algorithm for finding the optimal location of Static Var Compensator (SVC) to reduce the real power losses and to improve the voltage profile of a power system during single line outage contingencies. ABC algorithm is an optimization technique based on the intelligent behavior of honey bee swarms for foraging. Firstly, contingency ranking is performed using voltage performance index to determine the most severe line outage contingencies. Considering most severe contingencies one at a time, ABC algorithm has been applied to determine the optimal location and size of SVC. Effectiveness of the proposed method is demonstrated on IEEE 30- bus system.**

Keywords— ***Line Outage Contingency, FACTS Devices, SVC, Real Power Loss, Voltage Profile, VPI, ABC Algorithm***

I. Introduction

The electrical power system is continuously expanding in size and complexity all over the world. One of the most important issues in the electrical power system is to manage the reactive power. Flexible AC Transmission System (FACTS) devices play an important role in controlling the reactive power flow to the power network and the system voltage fluctuations [1]. FACTS devices are the solid state converters having capability of controlling various electrical parameters. Heavily loaded/ highly stressed condition of a power system or shortage of reactive power in a power system is the main reason to voltage collapse. Some incidents of system blackouts have been reported worldwide which occurred due to voltage collapse [2,3]. To save the system from voltage collapse, one way is to provide reactive power support with shunt FACTS devices at proper locations [1]. An adequate reactive power support is required to keep the power system under voltage secured condition.

The FACTS controllers can provide better transmission capability and fast and flexible power flow control [4]. Thyristor controlled series compensator (TCSC), static var compensator (SVC), static compensator (Statcom), thyristor controlled phase shifter transformer (TCPST), Unified power flow controller (UPFC) are some of the commonly used FACTS devices [5]. Out of these SVC and Statcom are shunt FACTS devices. Many methods have been addressed in the literature for allocation of shunt FACTS devices concerning the voltage profile and the reactive power reinforcement [6,7]. Several modern heuristic approaches and algorithms have been developed for finding optimal location of FACTS devices. Reference [8] uses Benders decomposition technique to find the optimal location of SVC to improve the voltage profile of a power system. In [9], optimal placement of SVC based on reactive power spot price is discussed. References [10-11] discuss about Simulated Annealing (SA) and genetic algorithm (GA) respectively to determine the location and size of SVC. The recently introduced Artificial Bee Colony (ABC) optimization algorithm is inspired by intelligent behavior of honey bees for foraging. Many approaches have been proposed to imitate the specific foraging behaviors of honey bee swarms and these techniques were applied for solving different types of problems.

This paper proposes ABC algorithm for determining the optimal location and sizing of SVC to reduce the real power loss and to improve the voltage profile of a power system for single line outage contingencies.

II. Modeling of SVC

SVC is a shunt FACTS device which is used to maintain the bus voltage of a power system at the desired level, to improve transient stability, for damping power oscillations and for compensation of reactive power [1]. It can inject or absorb reactive power at the connected bus. It can be modelled as a source or sink of reactive power. As Fig. 1 shows, the active power (P_{ij}) transmitted through a transmission line between bus *i* and bus *j* can be calculated as:-

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin \delta_{ij} \tag{1}$$

Where V_i and V_j are the voltages at bus *i* and *j*, X_{ij} is the reactance of the line; δ_{ij} is the angle between bus voltages V_i and V_j.

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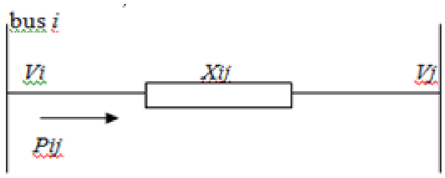

Figure1. Power flow between buses *i* and *j*

SVC can be mathematically modeled using susceptance model or firing angle model [1]. In the present paper, SVC susceptance model as shown in Fig. 2 has been used. From Fig. 2 the current and the reactive power injected are

$$I_{svc} = j\, B_{svc}\ V_k \quad (2)$$

$$Q_k = -V_k^{\,2}\ B_{svc} \quad (3)$$

Where Q_k, I_{svc} and B_{svc} are the injected reactive power, susceptance and injected current of SVC, respectively.

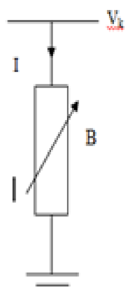

Figure2. Variable shunt susceptance model

III. Problem Formulation

The problem canvassed here is to find the optimal location and size of SVC which minimizes the active power loss and voltage deviation following severe single line outage contingencies. To determine the most severe line outage contingencies, contingency ranking is performed using voltage performance index (VPI). From the viewpoint of bus voltage violation limits, the severity of a contingency is evaluated by using VPI [12].

$$VPI = \sum_{i=1}^{all\ buses} \left(\frac{\Delta|V_i|}{\Delta|V_i^{max}|}\right)^{2m} \quad (4)$$

Where, $\Delta|V_i|$ is the difference between voltage magnitude for the line outage condition and base case voltage magnitude; $|V_i^{max}|$ is the value set by the utility engineer to limit a bus voltage from changing on an outage case. Here *m* is taken as 2.

A. To minimize the active power loss

The proposed ABC algorithm is used to minimize the real power losses by determining optimal location of SVC. The minimization in transmission loss is responsible for the redistribution of reactive power in the network. This in turn induces changes in the active power generated by the slack bus. To minimize the active power loss is the first objective which can be calculated using (5)

$$\min f_1 = \sum_{k=1}^{nl} g_k [V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)] \quad (5)$$

Where *nl* represents the number of transmission lines; g_k is the conductance of the *kth* line; $V_i\angle\delta_i$ and $V_j\ \angle\delta_j$ are the voltage of the *kth* line at the end buses *i* and *j*.

B. To minimize voltage deviations

The improvement in voltage profile of a power system is defined as the proximity of load bus voltage magnitudes from unity. SVC connected at appropriate location plays an important role in maintaining voltage profile. Therefore the second objective is to minimize the value of voltage deviation (VD). It is expressed as

$$\min f_2 = \sum_{i=1}^{nbus} |1 - V_i| \quad (6)$$

Where *nbus* is the total number of load buses in the power system and V_i is the voltage at bus *i*. Generally $\pm 5\%$ of voltage deviations from nominal values are acceptable.

C. Load Constraints

The real and reactive power balance equations must be satisfied at each node. The load constraints equations are expressed as:

$$g(x, u) = 0 \quad (7)$$

Using th Where g represents the equality constraints of a typical load flow equations. x is a vector of dependent variables consisting the power of slack bus P_{G1} , V_L voltage at the load bus and the reactive power outputs of generator Q_G, and *u* is a vector of independent variables consisting generator voltages V_G, real power outputs of generator P_G excluding the power of slack bus P_{G1} and shunt VAR compensations Q_C.

D. Operational Constraints

These constraints can be given as

$$h(x, u) \leq 0 \quad (8)$$

h represents the operating constraints of a power system including generator voltages, real and reactive power outputs and shunt compensation.The problem mentioned in section *3A* and *3B* form a nonlinear constrained multi-objective optimization problem, which are computed using equations (5) and (6) and can be formulated as

$$\min F = [f_1, f_2] \quad (9)$$

Subject to

$$g(x, u) = 0$$
$$h(x, u) \leq 0$$

In a multi-objective optimization problem, the two solutions x_1 and x_2 can have one of the two possibilities: either one dominates other or none dominates other. For minimization problem, a solution x_1 dominates x_2 if the following two conditions are satisfied:

1. $\forall i \in \{1,2\} : f_i(x_1) \leq f_i(x_2)$ (10)
2. $\exists j \in \{1,2\}: f_j(x_1) < f_j(x_2)$ (11)

If any of the above conditions gets violated, the solution x_1 does not dominate the solution x_2. If x_1 dominates the solution x_2, x_1 is called non-dominated solution. The solutions which are non-dominated within the entire search space are also known as Pareto-optimal solutions and form the Pareto-optimal set or Pareto-optimal front.

E. *Best Compromise solution*

Using the Pareto optimal set of non-dominated solutions, the method gives a single best compromise solution to the decision maker. Due to imprecise nature of decision maker's judgment, a membership function μ_i represents the i^{th} objective function F_i as follows:

$$\mu_i = \begin{cases} 1 & F_i \le F_i^{min} \\ \frac{F_i^{max} - F_i}{F_i^{max} - F_i^{min}} & F_i^{min} < F_i < F_i^{max} \\ 0 & F_i \ge F_i^{max} \end{cases} \quad (12)$$

Where F_i^{min} and F_i^{max} are the minimum and maximum values of the i^{th} objective function among all non-dominated solutions respectively. The normalized membership function μ^k, for each non-dominated solution *k*, is calculated as follows:

$$\mu^k = \frac{\sum_{i=1}^{N_{obj}} \mu_i^k}{\sum_{k=1}^{M} \sum_{i=1}^{N_{obj}} \mu_i^k} \quad (13)$$

Where M is the number of non-dominated solutions. The solution having maximum value of μ^k is being considered as the best compromise solution.

IV. ABC Algorithm

The Artificial Bee Colony algorithm was developed by D. Karaboga in 2005. It is a population based stochastic optimization algorithm which imitates the intelligent foraging behavior of honey bees swarms that how they find food sources[13]. This process makes them a good aspirant to develop a new search algorithm. In ABC algorithm, honey bees are divided into three groups of bees: employed bees, onlookers and scout bees.

In this algorithm the solution is determined by the position of the food sources and the nectar amount of food sources is expressed as the fitness value of the particular solution.

- Initializing new positions

In ABC algorithm, the random solutions are produced in the given range of variables θ_i (i = 1, 2………..S), where S is the number of food sources. In the next step, a new source for each employed bee, whose total food sources are equal to half of the total amounts, is produced by using (14)

$$x_{ij}(t+1) = \theta_{ij}(t) + \emptyset(\theta_{ij}(t) - \theta_{kj}(t)) \quad (14)$$

Where x is positions of onlooker bees at the t^{th} iteration, θ_k is the randomly chosen employed bee ,*k* is the index of the solution chosen randomly *(k* = int(rand ∗ SN) + 1), j = 1, . . ., D and D is the dimension of the problem and $\emptyset(.)$ is a series of random variables generated in the range of [-1 1].

- Probability to chose the nectar of food source

The preference of the food source to be chosen by an onlooker bee depends on the amount of nectar of food source. The probability *pi*, of the food source increases in accordance to the nectar amount. The probability *pi*, related with the food source can be calculated by the following expression (15)

$$p_i = \frac{fit_i}{\sum_{n=1}^{S} fit_n} \quad (15)$$

Where S is the number of food sources which is equal to number of employed bees, fit_i represents the fitness value of i^{th} solution which is proportional to the nectar amount of food sources in the position *i*.

- The Scout Bees

All the employed bees are distributed over the sources and the sources are checked to be discarded or not on the basis of the limit parameter. The employed bee associated with the discarded source becomes a scout and makes a random search in problem domain by using equation (16):

$$x_{ij} = x_j^{min} + (x_j^{max} - x_j^{min}) * rand \quad (16)$$

Where x_j^{max} and x_j^{min} are the maximum and minimum of the variables *j*. The value of rand is between 0 and 1.

Above are the steps followed until the stopping criterion in ABC is achieved, here maximum no. of cycles has chosen as stopping criterion.

A. *Computational Steps for ABC Algorithm*

The following steps are involved [13].

1. The positions of food sources are initialized.
2. A new food source is produced by every employed bee in her food source site and the better source is exploited.
3. On the basis of quality of solution the onlooker bee selects a source and produces a new food source in selected source site and exploits the better source.
4. The source to be abandoned is determined and its employed bee is allocated as scout bee for searching new food sources.
5. The food source which is found to be best is memorized.
6. The steps 2-5 are repeated until the stopping criterion is met.

V. Results and Discussion

To establish the effectiveness of the proposed ABC algorithm, it has been implemented on IEEE 30-bus system [14]. For the optimal placement and sizing of SVC the selection of contingencies and their ranking is done to analyze promptly those contingencies which cause the violation of voltage limits. To determine the severity of an outage in a power system, the VPI for various single line outages has been calculated using (4). For IEEE 30-bus system, out of 41 line outages Newton Raphson (NR) load flow method converged for37 line outages.

As per the VPI values, the most sever contingencies were observed to be line numbers 36, 37, 38, 25 and so on. Here, for

optimal placement and sizing of SVC, the three most critical line outage cases were considered. To implement the ABC algorithm for finding the optimal location and size of SVC, the following parameters of ABC algorithm are selected:
Colony Size = 6, Limit Parameter = 170, Maximum number of Cycles =180, Trials =20.

A. *For line outage 36*

For line outage 36, when SVC is not connected at any bus the losses were 0.1984 p.u. and the voltage deviation was 0.9642. In this case, 20 trials for ABC algorithm implementation to locate SVC optimally were carried out. During these trials, one of the four locations namely bus number 30, 29, 27 and 25 was obtained as the optimal location for SVC placement. The convergence characteristic has been shown in fig. 3 when optimal location of SVC was obtained as bus 29. The results obtained using ABC algorithm are shown in Table 1. As can be observed from Table 1, the minimum real power loss of 0.1925 p.u. was obtained with SVC placed at bus 25, but the voltage deviation was 0.72601 p.u. which is highest of all the four solutions. Also out of these four solutions no solution is best from the viewpoint of both the objectives PLoss and VD. These non-dominated solutions form the Pareto front and are depicted in fig. 4. The best compromise solution is calculated using (13), which provides optimal location of SVC as bus no. 27 with SVC rating of 0.1167p.u. The sixth row of Table 1 shows the value of best compromise (BC) solution that has maximum value of Fuzzy membership function (FMF) , at bus 27.

B. *For line outage 37*

For line outage 37, when no SVC was connected at any bus, the losses were 0.18006p.u. and voltage deviation was 0.7070p.u. For 20 trials one out of the four locations namely bus 30, 29, 22 and 19 was obtained as optimal location for placement of SVC. Fig. 5 shows the convergence characteristics when optimal location of SVC was found to be bus 29. Table 2 depicts the results obtained using ABC algorithm. As can be observed from Table 2, in this case also out of the four solutions no solution is best from the viewpoint of both the objectives PLoss and VD. The best compromise solution provides optimal location of SVC as bus no. 29 with SVC rating of 0.03581p.u.

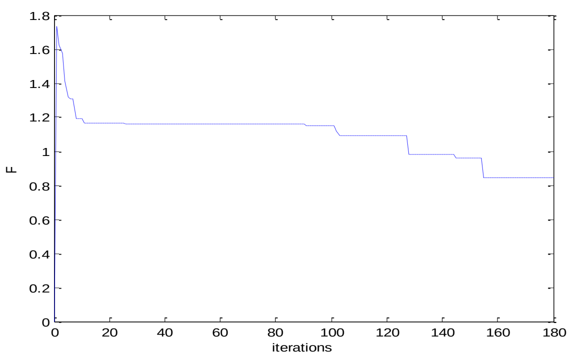

Figure3. ABC convergence characteristic for line outage 36

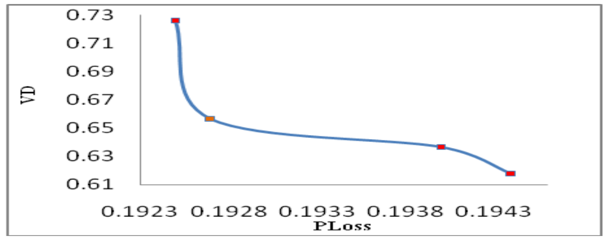

Figure4. Pareto optimal front for line outage 36

TABLE I. VOLTAGE PROFILE FOR LINE OUTAGE 36

	Without SVC	With SVC at			
Bus No.	---	***Bus 30***	***Bus 29***	***Bus 27***	***Bus 25***
PLoss	0.1984	0.1944	0.1940	0.1927	0.1925
VD	0.9642	0.6180	0.6368	0.6565	0.72601
SVC Rating	---	0.1104	0.1052	0.1167	0.1195
FMF		0.2186	0.2265	**0.3363**	0.2186
BC Solution	----	At bus 27 with SVC rating 0.1167p.u.			

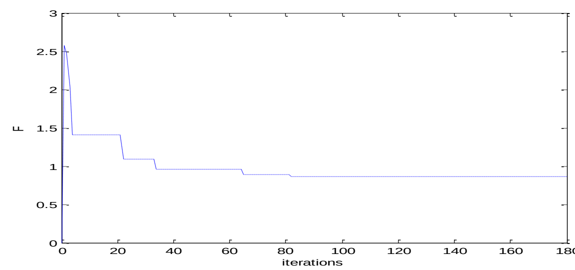

Figure 5. ABC convergence plot for line outage 37 SVC at bus 29.

TABLE II. VOLTAGE PROFILE FOR LINE OUTAGE 37

	Without SVC	With SVC at			
Bus No.	---	***Bus 30***	***Bus 29***	***Bus 22***	***Bus 19***
PLoss	0.18006	0.1789	0.1791	0.1845	0.1827
VD	0.70700	0.67993	0.66675	0.45962	0.5539
SVC Rating	------	0.04221	0.03581	-0.21755	-0.1033
FMF	------	0.2617	**0.2558**	0.2267	0.2558
BC Solution	----	At bus 29 with SVC rating 0.03581p.u.			

C. *For line outage 38*

For line outage 38, Table 3 when no SVC was connected at any bus, the losses were 0.1813p.u. and voltage deviation was 0.6902p.u. For 20 trials one out of the four locations namely bus 30, 29, 21 and 19 was obtained as optimal location for placement of SVC. Fig. 6 shows the convergence characteristics when optimal location of SVC was found to be bus 30. Table 3 shows the results obtained using ABC algorithm. In this case, the best compromise solution provides optimal location of SVC as bus no. 30 with SVC rating of 0.0485p.u.

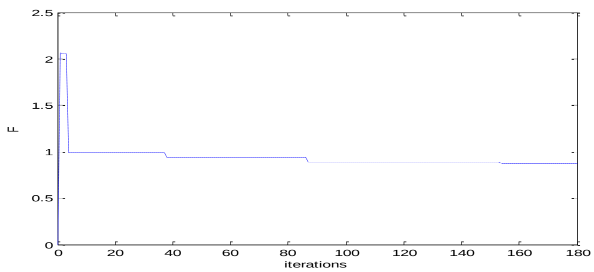

Figure6. ABC convergence plot for line outage 38 SVC at bus 30.

TABLE III. VOLTAGE PROFILE FOR LINE OUTAGE 38

	Without SVC	**With SVC at**			
Bus No.	---	***Bus 30***	***Bus 29***	***Bus 21***	***Bus 19***
PLoss	0.1813	0.1802	0.1804	0.1858	0.1840
VD	0.6902	0.6890	0.6856	0.45018	0.544
SVC Rating	---	0.0485	0.03003	0.21463	-0.1029
FMF	----	**0.2559**	0.2559	0.2377	0.2504
BC Solution	----	At bus 30 with SVC rating 0.0485p.u.			

VI. Conclusion

This paper presents the application of ABC algorithm for optimal placement and sizing of SVC for loss minimization and voltage profile improvement during single line outage contingencies. This multi-objective optimization problem was converted into a single objective problem and was handled by giving equal importance to each of them. Various trials of ABC algorithm implementation provided different optimal locations for SVC placement, but no solution was best from the viewpoint of both the objectives PLoss and VD. Fuzzy based mechanism was employed to obtain the best compromise solution. The results clearly demonstrate the efficiency of the ABC algorithm for solving multi-objective problem and can be implemented in large-scale power systems also.

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