Application of Multi-Objective Technique to Incorporate UPFC in Optimal Power Flow using Modified Bacterial Foraging Technique

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ABSTRACT

A modified bacterial foraging technique is applied to solve the multi-objective optimal power flow problem with unified power flow controller (UPFC). The introduction of UPFC in power system improves the stability and it is one of the crucial factors for effective modern power systems. Effective means for controlling and improving power flow is done by installing fast reacting devices such as a Unified Power Flow Controller (UPFC).The application of modified bacterial foraging technique is applied to find optimal location of unified power flow controller to achieve solution of optimal power flow and this problem is formulated by multi-objective optimization using bacterial foraging technique. The optimal power flow problem is used to minimize the overall cost functions, which include the total active and reactive production cost function of the generators and installation cost of UPFCs and also the OPF constraints are generators, transmission lines and UPFCs limits are included. Modified Bacterial foraging algorithm and multi-objective optimization technique is applied to the problem with use of controllable UPFC devices is proposed. The specified power flow control constraints due to the use of UPFC devices are included in the OPF problem in addition to these normal conventional constraints. The sensitivity analysis is carried out for the location of UPFC devices. This provides an enhanced economic solution with the use of controllable of UPFC devices. Simulations are performed modified IEEE 4 bus and IEEE 30 bus system for optimal location of UPFC and the results obtained are encouraging and will be useful in electrical restructuring.

General terms:
Algorithm, Optimization, Implementation

Keywords:
Unified power flow controller (UPFC), modified bacterial foraging and optimal power flow.

1. INTRODUCTION

With the ever-increasing complexities in power systems across the globe and the growing need to provide stable, secure, controlled, economic, and high-quality electric power especially in today's deregulated environment. The unified power flow controllers (UPFC) devices are going to play a critical role in power transmission systems [1]. There are a variety of methods proposed for optimizing the placement of UPFC devices [3]–[7]. The Unified Power Flow Controller (UPFC) is the most powerful, but also the most expensive, device in the family of voltage-source-converter-based FACTS devices, but there are very few researches that suggest a simple and reliable method [5]–[7]. For determining the suitable location of UPFCs for enhancing the loadability of the power system over different topologies. The main purpose of OPF is to determine the optimal operation state of a power system while meeting some specified constraints. Unified power flow controllers devices become more competitive. They may be used to improve the transient responses of power systems and also control the power flow i.e. both real and reactive power. The main advantages of UPFC are the ability in enhancing system and increasing the loadability [1] and will treat the solution in modern and deregulated power systems issues.

In the state operation of power system, unwanted loop flow parallel power between utilities is problems in heavily loaded interconnected power systems. These two power flow problems are sometimes beyond the control of generators or it may increase cost too much with generator regulations. However, with UPFC controllers, the unwanted power flow can be easily regulated [3] [6].In OPF the main objective is to minimize the costs of meeting the load demand for the power system while satisfying all the security constraints [4].since OPF is a non-linear problem, decouple of the control parameter of the facts device is a highly nonlinear problem so bacterial foraging technology gives solution for these types of non-linear problem.

The modified bacterial foraging technique approach handles the multi-objective optimization [2] with many objectives and constraints included. In this problem the installation cost, reactive power production and optimal location of UPFC devices are considered. So this problem is formed and formulated in multi-objective manner and here the modified bacterial foraging is applied for this multi-objective optimization problem. Population based co-operative and competitive stochastic search algorithms are very popular in the recent years in the research area of computational intelligence. In this, some well established search algorithm such as Genetic algorithm (GA) and evolutionary programming are successfully implemented to solve the complex problems. In addition to this the modified bacterial foraging technique also very effective to solve various complex problems in electrical engineering and it gives better optimal results compare to other search algorithms.

In this work, the conventional OPF problem is solved with modified bacterial foraging technique and compared with GA.GAs also robust search based optimization algorithms

[13]. Thus the proposed algorithm identifies the optimal value of control settings of UPFC, UPFC device constraints; power balance constraints and the output of objective are minimized. This approach minimize total the cost as well as iteratively evaluates the control settings of UPFC that are needed to maintain specified line flows and the sensitivity analysis is carried to position the UPFC in test system The effectiveness of the proposed approach is demonstrated through IEEE 4 and IEEE 30 bus system.

2. PROBLEM FORMULATION

In this work, the consideration UPFC device along with optimal power flow problem is treated as optimization problem and it is formulated as a multi-objective optimization manner, they are minimizing the total cost of operating the spatially separated generating units subject to the set of equations that characterize the flow of power through the system and all operational, security constraints and UPFC constraints [6].

2.1 Objective Functions

Objective functions are the (1) minimize generation costs of power plants and (2) installation cost of UPFC.

2.1.1 Minimize generation costs of power plants

To minimize the generation cost of power plant

$$F(X)=\sum_{i=1}^{NG} C_{gpi}(P_{gi}) + C_{gqi}(Q_{gi}) + \sum_{j=1}^{N} C^{t}_{UPFCi} \quad (1)$$

$$C_{gpi}= (a_i P_{Gi}^2 + b_i P_{Gi} + c_i) \quad (2)$$

2.1.2 Installation cost of UPFC

To minimize the installation cost of UPFC

$$C^{t}_{UPFCj}=(C_{UPFCj}\times S_j\times 1000\times \alpha)/8760 \quad (3)$$

$$CUPF_{Cj}=0.0003S_j^2 - 0.2691S_j+188.22 \quad (4)$$

$$\alpha=\frac{r(1+r)^n}{(1+r)^n-1} \quad (5)$$

Where,

C^{t}_{UPFCj} =cost of installation of UPFC in $\$h^{-1}$.
C_{UPFCj} =cost of installation of UPFC in $/KVAR.
S_j =operating range of FACTS devices in MVAR.
α = the capital recovery factor (CRF).
r = the interest rate.
n = the capital recovery plan.

Considering the interest rate r=0.05, the capital recovery period n=10 years, the capital recovery factor can be computed, i.e., α=0.1295.The cost of reactive power production can be modeled using opportunity cost calculation [8]. An approximation for cost of reactive power production is,

$$C_{gqi}(Q_{gi})=[C_{gpi}(S_{gimax}) - C_{gpi}\sqrt{S_{gimax}^2 - Q_{gi}^2}]\, K \quad (6)$$

Where

S_{gimax}=operating range of the generator in bus i.
K =benefit factor of reactive power production selected

2.2 Constraints

Several restrictions have to be modeled in mathematical solutions are in line with planning requirements. Here the objective function is solved with the equality and in-equality constraints.

2.2.1 Voltage Stability Constraints

Voltage Stability includes voltage stability constraints in the objective function and is given by,

$$VS = \begin{cases} 0 & \text{if } 0.9<V_b<1.1 \\ 0.9-V_b & \text{if } V_b>0.9 \\ 1.1-V_b & \text{if } V_b>1.1 \end{cases} \quad (7)$$

Where
V_b= Voltage at bus b

2.2.2 UPFC Devices Constraints

The UPFC device limit is given by,

$$-0.5X_L<X_{TCSC}<0.5X_L$$
$$-200MVAR<Q_{SVC}<200MVAR \quad (8)$$

Where
X_L = original line reactance in p.u
X_{TCSC} =reactance added to line
Q_{SVC} = reactive power injected at SVC placed bus in MVAR

2.2.3 Power balance constraints

While solving the optimization problem, power balance equations are taken as equality constraints. The power balance equations are given by,

$$\sum P_G = \sum P_D + P_L \quad (9)$$

Where
$\sum P_G$ =Total power generation
$\sum P_D$ =Total power demand
P_L =Losses in the transmission network

$$P_i= \sum |E_i||E_K|[G_{ik}\cos(\theta_i-\theta_k) + B_{ik}\sin(\theta_i - \theta_k) \quad (10)$$
$$Q_i= \sum |E_i||E_K|[G_{ik}\sin(\theta_i-\theta_k) + B_{ik}\cos(\theta_i - \theta_k)$$

Where
P_i = Real power injected at bus i.
Q_i = Reactive power injected at bus i.
(θ_i, θ_k) = The phase angles at buses i and k
E_i,E_k = Voltage magnitudes at bus i and k

2.2.4 Real and reactive power constraints

$$P_{gi}^{min}\leq P_{gi}\leq P_{gi}^{max} \quad (11)$$
$$Q_{gi}^{min}\leq Q_{gi}\leq Q_{gi}^{max} \quad (12)$$

Where
P_{gi} = Real power injected at bus i.
Q_{gi} = Reactive power injected at bus i

2.2.5Tap setting transformer constraints

$$T_{gi}^{min}\leq T_{gi}\leq T_{gi}^{max} \quad (13)$$

2.3 Particle Representation

Bacterial foraging technique requires the parameters of the optimization problem. Since the goal of optimization was to allocate the UPFCs, taking variables control to select this parameters. A particle is represented with the following strings of variables control,

$$Z= [V_1 \quad P_{g2}....P_{g\,N} \quad P_{sp1}....P_{spN} \quad Q_{ip1}........Q_{spN}\, V_{vrtar1}.....V_{vrtarN}$$
$$UPFCnl_1.....UPFCnl_N \quad UPFCside_1......UPFCside_N]$$

Where

V_1 = the voltage magnitude of main bus.

P_{gi} = the active power generations at bus *i*.

P_{spi}, Q_s = the active and reactive powers leaving of UPFC i

$UPFCside_i$ = status of install UPFC

$UPFC_{nli}$ = number of compensated transmission line with UPFC i

3. MULTI- OBJECTIVE OPTIMIZATION

Multi-objective Optimization (MOO) problems are defined as those problems "where two or more, sometimes competing and/or incommensurable, objective functions have to be minimized simultaneously". In general, for a problem with n objective functions, the multi-objective formulation can be as follows

Minimize/maximize $f_i(x)$ for i=1, 2, 3...n

Subject to

$$G_j(x) \leq 0 \quad j=1, 2...J$$
$$H_k(x) = 0 \quad k=1, 2...K \qquad (14)$$

Often the multi-objective is combined into a single objective so that optimization and mathematical methods can be used. There are n objectives and p variables so f(x) is an n dimensional vector and x is a p dimensional vector corresponding to p decisions or variables, solutions to a multi-objective optimization problem are often mathematically expressed in terms of nondominated or superior points. We say in maximization problem that x dominates y if

$$f_i(x) \geq f_i(y) \;\; \forall \text{ i and } f_i(x) > f_i(y)$$

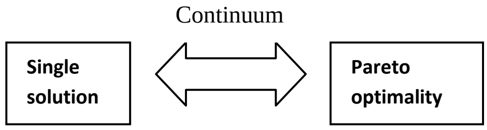
for at least one i $i \in \{1,2...n\}$;

Similarly, for a minimization problem dominates y if

$$f_i(x) \leq f_i(y) \;\; \forall \text{ i and } f_i(x) < f_i(y)$$

As a result, algorithms are used to resolve, these problems have to be able to provide more than one solution. One way is to use a Weights Aggregating approach (WA) technique; Weights can either be fixed or not. Alternatively, population-based algorithms, such as Evolutionary Algorithms (EA) or the bacterial foraging can be used without defining a combined function. Finding the Pareto Optimal set can be performed by several runs of the algorithm providing a single Pareto Optimal point each time. Generally the two most common approaches to solve multiple objectives are: combine them into a single objective function and obtain a single solution, obtain set of non-dominated Pareto optimal solutions. Thus there is a need to bridge the gap between single solutions and Pareto optimal sets.

The Pareto set includes all rational choices, among which the decision maker has to select the final solution by trading the objectives against each other. The search is then not for one optimal solution but for a set of solution that are optimal in a border sense. There are a number of techniques to search the solution for Pareto optimal solutions. The objective of this search is to achieve this balance, by introducing two practical methods that reduce the Pareto optimal set to achieve a smaller set called the "pruned pareto set".



4. MODIFIED BACTERIAL FORAGING

The bacterial foraging technique which is tailored for optimizing difficult numerical functions and based on metaphor of human social interaction. Its paradigm be implemented in simple in simple form of computer codes and is computationally inexpensive in terms of both memory and speed.

Nowadays Bacteria Foraging technique is gaining importance in the optimization problems. Because search strategy of bacteria is salutary (like common fish) in nature and Bacteria can sense, decide and act so adopts social foraging (foraging in groups). A group of bacteria move in search of food and away from noxious elements, a biological method known as foraging [2]. All bacteria try to move upward the food concentration gradient individually. At the initial location they measure the food concentration and then tumble to take a random direction and swim for a fixed distance and measure the concentration there. This tumble and swim make one chemo tactic step. If the concentration is greater at next location then they take another step in that direction [10][11][12]. When concentration at next location is lesser that of previous location they tumble to find another direction and swim in this new direction. This process is carried out up to a certain number of steps, which is limited by the lifetime of the bacteria. At the end of its lifetime the bacteria that have gathered good health that are in better concentration region divide into two cells. Thus in the next reproductive step the next generation of bacteria start from a healthy position. The better half reproduces to generate next generation where as the worse half dies. This reproduction step is also carried out a fixed number of times. In the optimization technique we can take the variable we want to optimize as the location of bacteria in the search plane. The specifications such as number of reproductive steps, number chemo tactic steps which are consisted of run (or swim) and tumble, swim length, maximum allowable swims in a particular direction [2][11][12]are given for a particular problem then the variable can be optimized using this modified bacteria Foraging Optimization technique.

5. ALGORITHM

Step1: Initialization

Variables needed for the algorithm are initialized. They include the following

i. Number of parameters (p) to be optimized.

ii. Number of bacteria (S) to be used in the search.

iii.Swimming length Ns after which tumbling of bacteria will be undertaken in a chemotactic loop.

iv.Nc the number of iteration to be undertaken in a chemotactic loop. (Nc > Ns).

v.N_{re} the maximum number of reproduction to be undertaken.

vi.N_{ed} the maximum number of elimination and dispersal events to be imposed over the bacteria to find optimal settings to get the solution of power flow.

vii.P_{ed} the probability with which the elimination and dispersal will continue according to objective the function.

Step 2: Elimination–dispersal loop: l = l+1.

Step 3: Reproduction loop: k = k+1.

Step 4: Chemo taxis loop: j = j+1.

Sub step a: $\forall i$ =1, 2...S, calculate cost function *J* (*i*, *j*, *k*, *l*)

Sub step b: Find the Global Minimum bacteria θgm from the cost functions evaluated till that point.

Sub step c: Tumble: generate a random vector $\Delta(i) \in R^n$ with each element $\Delta_m(i)$, m = 1, 2,. . . ,p, a.

Sub step d: Move: Let,

$$\emptyset^x(i+1,j,k) = \emptyset^x(i,j,k) + c(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \qquad (15)$$

Sub step f: Compute J (i, j+1, k, l).

If generation cost and installation cost is minimize then go to next step else go to step 4.

Step 5: swim

i. Let m=0 (counter for swim length)

ii. While m<N_s (have not climbed down too long)

- Let m=m+1
- If Jsw(*i*, *j*+1, *k*, *l*)< J_{last} (if doing better), let

$$\emptyset^x(i+1,j,k) = \emptyset^x(i,j,k) + c(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

use $\emptyset^x(i+1,j,k)$ to compute the new J (*i*, *j*+1, *k*, *l*).

iii. Go to next bacterium (*i*+1) if $i \neq S$, to process the next bacterium.

Step 6: If j < N_c, go to step 3. In this case, continue chemotaxis, since the life of the bacteria is not over.

Step 7: Reproduction

i. For the given *k* and *l*, and for each *i*=1, 2…S, let

$$J^i_{health} = \min \{ J_{sw}(i, j, k, l) \}$$

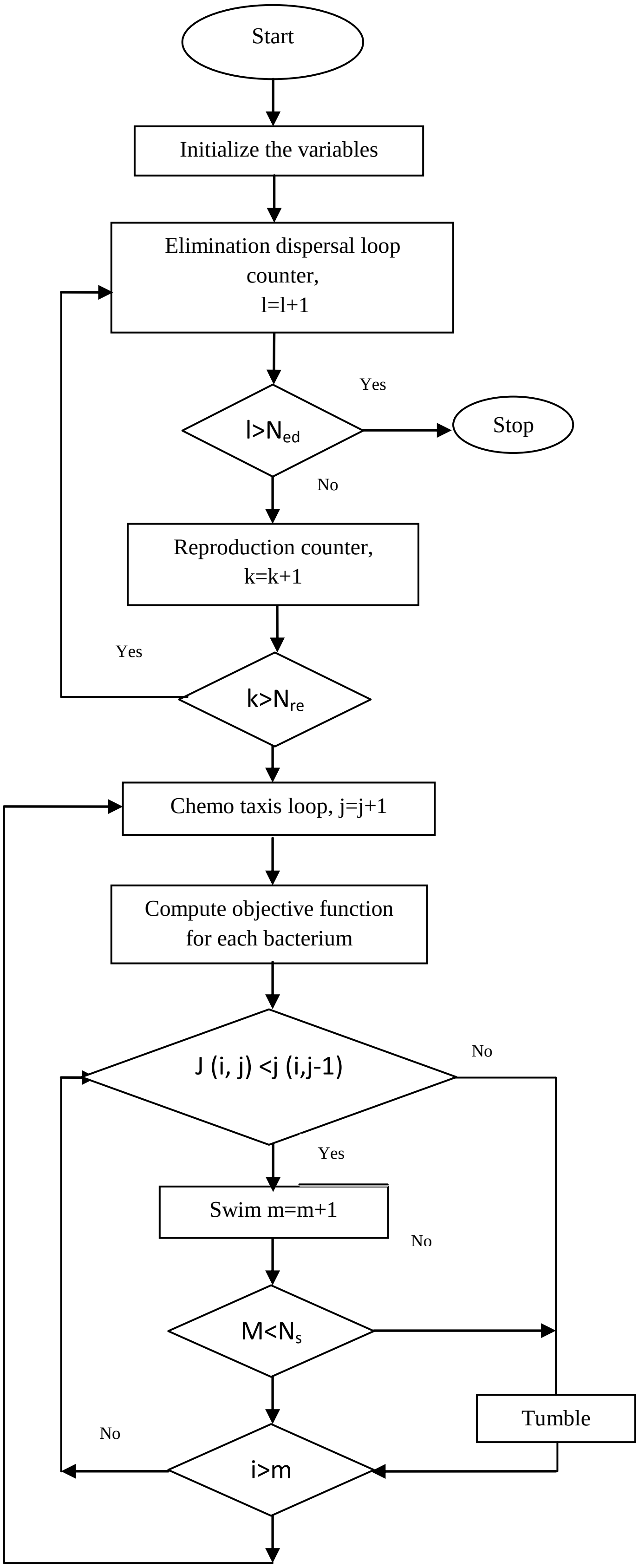
be the health of the bacterium i. Sort bacteria in order of ascending cost J_{health} (higher cost means lower health).

ii. The Sr=S/2 bacteria with highest J_{health} values die and other Sr bacteria with the best value split.

Step 8: If k < Nre, go to [step 3]. In this case, we have not reached the number of specified reproduction steps so we start the next generation of the chemotactic loop.

Step 9: Elimination-dispersal: For *i*=1, 2,..S, with probability P_{ed}, eliminates and disperses each bacterium to random location on the optimization domain.

6. FLOWCHART



7. RESULTS AND DISCUSSIONS

The optimization of the controller parameters is carried out by evaluating the multi-objective functions. The effectiveness of proposed approach is tested using IEEE 4-bus and IEEE 30 bus system. The test network was tested without UPFC and with UPFC to find the installation cost as well as generation cost.

7.1 IEEE 4-bus test system

The optimal power flow is first tested on IEEE 4-bus system. System data and results are based on a 100 MVA and bus 1 is the reference bus. In order to verify the presented models it is compared with GA. In table 2 the case1, case2, case3 are the results of without UPFC, GA, and proposed technique bacterial foraging. To have better optimal power flow it is necessary to compare the results. Here, only total active generation cost is taken as the objective function for this test system to find optimal location of UPFC.

The data for the UPFC are: $X_{cR}= 0.1$, $X_{vR} =10$, $0\leq V_{cR} \leq 0.1$, $0\leq V_{vR} \leq 1.1$, $0\leq \theta_{cR}\leq 2\pi$, $0\leq \theta_{vR}\leq 2\pi$.

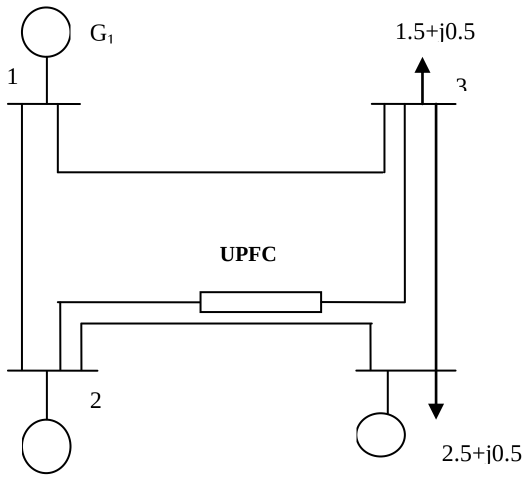


Figure 1: IEEE 4-bus test system

Table 1: Generator data for 4-bus test system

G_i	a_i	b_i	c_i	P_{gi}^{min} (p.u)	P_{gi}^{max} (p.u)	Q_{gi}^{min} (p.u)	Q_{gi}^{mas} (p.u)
G_1	230	110	0.007	0.5	4	-1.2	1.2
G_2	200	10	0.005	0.5	3.5	-1.2	1.2
G_3	240	12	0.009	0.5	3.5	-1.2	1.2

Table 2: Results of IEEE 4-bus test system

Variable	Case 1	Case 2	Case 3
Total cost $/hr	5481.3	5540.4	5277.9
P_{g1}	0.9413	1.3602	0.9703
Q_{g1}	0.2544	0.7826	0.3526
P_{g2}	2.4449	1.6872	2.3557
Q_{g2}	0.1762	-0.2250	0.6927
P_{g3}	0.6343	0.7696	0.6998
Q_{g3}	0.9769	4.160	0.4453
UPFC P_g	S.E:----- R.E:-----	S.E:0.756 R.E:0.749	S.E:0.8798 R.E:-0.8798
UPFC Q_g	S.E:----- R.E:-----	S.E:0.316 R.E:-0.215	S.E:0.2388 R.E:-0.1921

Where,

S.E: sending end voltage
R.E: receiving end voltage

The results of case 1 are the results of the traditional economic dispatch which show a total generation cost of 5481.3 $/h. For this case, line 2–3 would carry more than its limit and most of the load is served by G2 without utilizing UPFC.When UPFC is placed between buses 2 and 3 near bus 1, a cheaper dispatch is obtained by modified bacterial foraging technique where the total cost has been reduced.

7.2 IEEE standard 30-bus system

The modified IEEE 30-bus test system also is used to verify the effectiveness of the proposed algorithm.

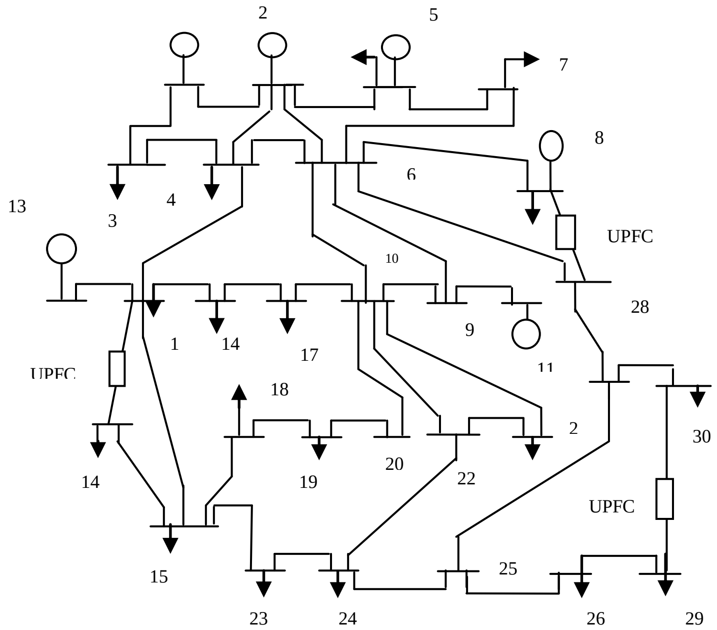


Figure 2: IEEE 30-bus system

Table 3: Generator data for IEEE 30-bus system

G_i	a_i	b_i	c_i	P_{gi}^{min} (p.u)	P_{gi}^{max} (p.u)	Q_{gi}^{min} (p.u)	Q_{gi}^{mas} (p.u)
G_1	100	15	0.002	0.3	2	-0.5	0.5
G_2	100	10	0.001	0.2	2.7	-0.8	1
G_5	100	20	0.005	0.4	2	-0.7	0.8
G_8	100	30	0.003	0.2	2	-0.8	0.7
G_{11}	100	20	0.005	0.2	2.5	-0.8	0.8
G_{13}	100	10	0.002	0.3	2.7	-0.7	0.7

Table 4: Results for IEEE 30-bus system

P_{gi}(MW)	Case1	Case2	Case3
P_{g1}(MW)	170.1	173.64	170.63
P_{g2}(MW)	53.7	47.79	55.26
P_{g5}(MW)	20.8	21.78	25.04
P_{g8}(MW)	18.85	23.03	11.50
P_{g11}(MW)	12.05	12.52	18.10
P_{g13}(MW)	17.6	11.50	14.53
$\sum P_{gi}$(MW)	293.1	290.26	295.03
$\sum$cost($/hr)	805.637	802.92	801.910

Without UPFC the cost of OPF is 805.637 and Cost of OPF with UPFC using GA and modified bacterial foraging is 802.92 and 801.910 respectively. The results show that the generation cost of the unit has been reduced in bacterial foraging when compare to that of GA.This shows the potential of the bacterial foraging algorithm.

Two set of test runs are performed, the first (GA) with only the basic GA operators and the Second bacterial foraging. The operating cost of bacterial foraging for OPF solution is slightly less than the GA.

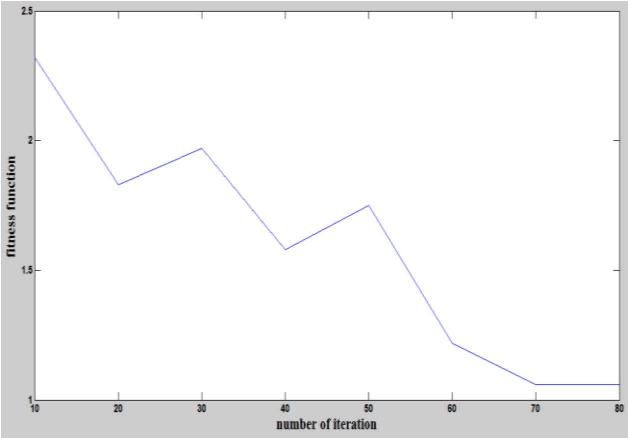


Figure 3: Fitness calculation for population

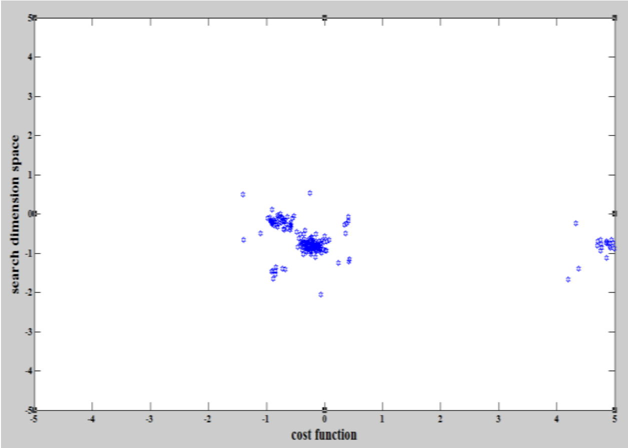


Figure 4: Particle search in iteration 1

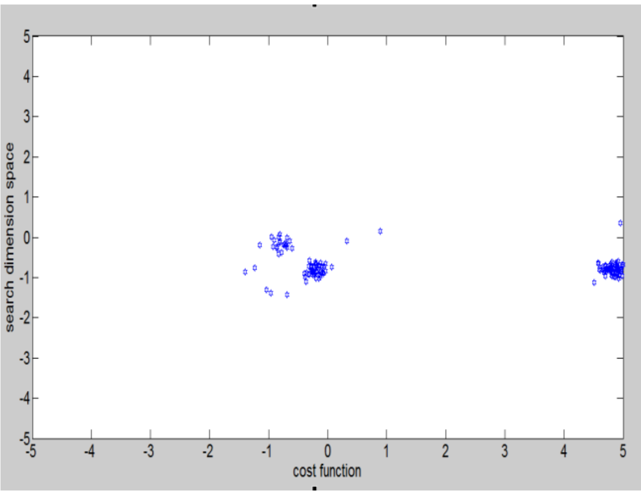


Figure 5: Particle search in iteration 2

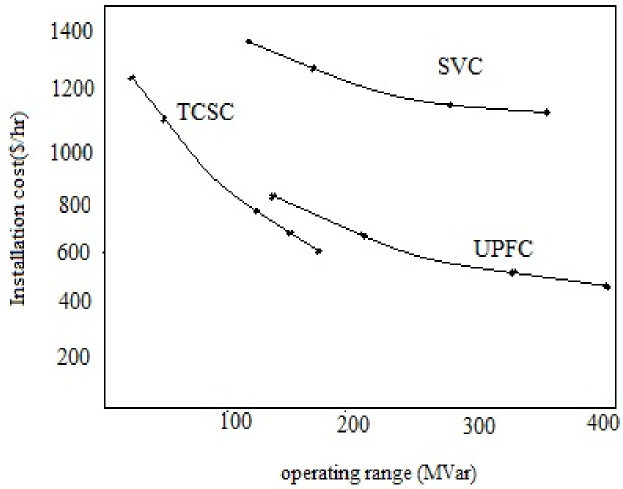


Figure 6: Installation cost curve of UPFC

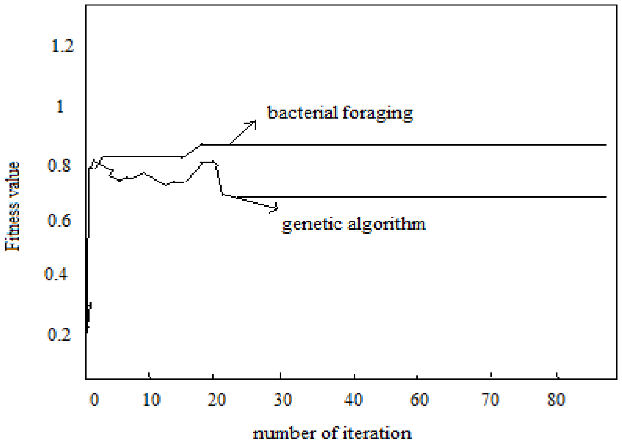


Figure 7: Comparison of results

8. CONCLUSION

From the results it is clear that UPFC is the most powerful device while comparing other devices and UPFC effectively reduces the losses up to 89-90% of the total loss. TCSC and SVC reduces the losses up to 75%The proposed method introduces the injected power model of UPFC devices into a conventional AC optimal power flow problem to exploit the new characteristic of UPFC devices. In this method, modified bacterial foraging effectively finds the optimal setting of the control parameters by using the OPF method. It also shows that the modified bacterial foraging technique is well suitable to deal with non-smooth, non-continuous, non-differentiable and nonconvex problem, such as the optimal power flow problem with UPFC.

Thus this paper presents the application of multi-objective optimization of modified bacterial foraging technique to find the optimal location of UPFCs for getting minimum total active and reactive power production cost of generators and to minimize the installation cost of UPFCs. The UPFC can provide control of voltage magnitude, voltage phase angle and impedance. Therefore, it can be utilized to effectively increase power transfer capability of the existing power transmission lines, and reduce operational and investment costs.

Simulations were performed on IEEE-4 bus and IEEE 30 bus system. Optimizations were performed on the control parameters including the location of the UPFCs and their settings in the line. Results show that utilizing UPFC may reduce generation costs. The modified bacterial foraging technique with multi-objective optimization technique gives minimum cost of power production and installation of UPFC when compared with genetic algorithm

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