Hybrid Bat Optimization Algorithm with Differential Evolution Strategy for Non-Smooth Optimal Power Flow

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Abstract- *Optimal Power Flow is the special case of power flow problems with an objective of optimizing the power system operation and planning. Recently, the problem of OPF has received much attention by many researchers. The main aim of this work is optimizing the fuel cost and it is done by properly setting the real power generation from the generators, generator bus voltages, transformer tap settings and SVC settings in a power system. In this work, OPF is achieved by considering the general quadratic function and valve point effect (i.e) fuel cost minimization is done in both smooth and non-smooth case of power system. The bio inspired hybrid Bat Algorithm with the Differential Evolution (BADE) is the optimization algorithm used for optimally setting the values of the control variables. The BADE is a recently developed algorithm and is with less number of operators and easy to implement. The algorithm can be coded in any programming language easily. The proposed algorithm is to be tested on the standard IEEE-30 bus system and the results are found to be better than that of the other algorithms reported in the literature.*

Keywords- Optimal power flow, bio inspired algorithm, smooth case, non-smooth case, valve point effect and quadratic function

I. INTRODUCTION

systems has done to maintain the system stability, security and economy. Optimal power flow (OPF) has become one of the most important problems and the main objective of the OPF problem is to optimize a chosen objective function through optimal adjustments of power systems control variables while at the same time satisfying system operating conditions with power flow equations and inequality constraints. The equality constraints are the nodal power balance equations, while the inequality constraints are the limits of all control or state variables. In general the OPF problem is large-scale, highly constrained, nonlinear and non-convex optimization problem.

The OPF is the fundamental tool that enables electric utilities to specify economic operating and secure states in power systems. The concept of OPF was first proposed by Dommel and Tinney. Their theory was the initial proposal for the optimization concept. Later it gained popularity by many researchers A wide variety of optimization techniques have been applied in solving the OPF problem such as non-linear programming, Quadratic Programming, Linear Programming, Newton based methods, Sequential unconstrained minimization technique, interior point methods, Genetic Algorithm, Evolutionary Programming. Even though, excellent advancements have been made in classical methods, they suffer with the some disadvantages. It is necessary to find new optimization methods that are capable of overcoming these drawbacks. Recently, many population-based optimization techniques have been used to solve complex constrained optimization problems. These techniques have been increasingly applied for solving power system optimization problems such as economic load dispatch, optimal reactive power flow and OPF in decades. Some of the population-based methods have been used for solving the OPF problem successfully, such as tabu search, particle swarm optimization, differential evolution algorithm, evolutionary programming, ant colony algorithm, fire fly algorithm, big bang-big crunch, fruit fly algorithm and harmony search algorithm.

Recently, a new evolutionary computation technique, called Hybrid bat algorithm with differential evolution strategy (BADE) has been proposed. This optimization method provides better result for OPF problems. After formulating the OPF problems, programming work is carried out in Matlab and comparison with other algorithm were done. A case study on an IEEE-30 bus system expresses some sound idea in a very positive result oriented manner directed towards the applicability of the proposed approaches in the practical electrical network system.

II. PROBLEM FORMULATION

The goal of a solution of optimal power flow problem is to minimize the total production cost through optimal adjustment power system control parameters while satisfying equality and inequality constraints at the same time.

The OPF problem can be mathematically formulated as follows:

$$Minf(x,u) \qquad (1)$$

$$s.tg(x,u) = 0 \qquad (2)$$

$$h(x,u) \le 0 \qquad (3)$$

$$u\epsilon \cup \qquad (4)$$

$$where\ x = [\delta^T, V_L^T]^T$$

x is a state vector of the system with bus bar angles δ and load bus voltages v_L. u is the control variables to optimize equation 1 are real power generation of generator loading units (P_g), terminal voltages of generators (V_g), tap-setting of transformers (t_{tap}) and switchable shunts (Q_{sh}).

$$u = \left[P_g^T, V_g^T, t_{tap}^T, Q_{sh}^T\right] \qquad (5)$$

Equation (1) is considered as sum of quadratic cost functions of thermal generating real power loading units with usual a_i, b_i, c_i cost coefficients.

$$F_T\left(P_g\right) = \sum_{i=1}^{Ng} a_i + b_i P_{gi} + c_i P_{gi}^2 \quad \frac{\$}{h} \qquad (6)$$

This objective is subjected to the following constraints.

2.1Equality constraints

(i) Active power balance in the network

$$P_{gi} - P_{di} - v_i \sum_{j=1}^{NB} v_j\left[G_{ij}cos\left(\delta_i - \delta_j\right) + B_{ij}sin\left(\delta_i - \delta_j\right)\right] = 0$$

$$(i = 1,2,3,\ldots\ldots\ldots NB) \qquad (7)$$

(ii) Reactive power balance in the network

$$Q_{gi} - Q_{di} - v_i \sum_{j=1}^{NB} v_j\left[G_{ij}sin\left(\delta_i - \delta_j\right) - B_{ij}cos\left(\delta_i - \delta_j\right)\right] = 0$$

$$(i = NG + 1,\ldots\ldots NB) \qquad (8)$$

where V_i and V_j are the voltages of ith and jth bus, respectively, NB is the number of buses, P_{Gi} is the active power generation, Q_{Gi} is the reactive power generation, P_{Di} is the active load demand, Q_{Di} is the reactive load demand, G_{ij}, B_{ij} and d_{ij} are the conductance, susceptance and phase difference of voltages between bus i and bus j, respectively.

2.2Inequality constraints

(i) Active power generation of generator buses

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \qquad (i = 1,2,\ldots\ldots NG) \qquad (9)$$

(ii) Limits on voltage magnitudes of generator buses

$$V_{gi}^{min} \le V_{gi} \le V_{gi}^{max} \qquad (i = 1,2,\ldots\ldots NG) \qquad (10)$$

(iii) Limits on switchable shunts

$$Q_{shi}^{min} \le Q_{shi} \le Q_{shi}^{max} \qquad (i = 1,\ldots\ldots NSH) \qquad (11)$$

(iv) Limits on tap setting of transformers

$$t_{tap}^{min} \le t_{tap} \le t_{tap}^{max} \qquad (i = 1,\ldots\ldots. NT) \qquad (12)$$

Equation (3) has functional operating constraints which are as follows

(i) Limits on reactive power generation of generator buses

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \qquad (i = 1,2,\ldots\ldots NG) \qquad (13)$$

(ii) Limits on voltage magnitudes of load buses

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \qquad (i = NG + 1,\ldots NB) \qquad (14)$$

(iii) Thermal limits of transmission lines

$$|MVA|_i \le MVA_i^{max} \qquad (i = 1,\ldots\ldots. NL) \qquad (15)$$

Inclusion of penalty terms $P_s, P_{Vi}, P_{Qi}, P_{Li}$ for slack bus generator MW limit violation, Load bus voltage limit violations, generator reactive power limit violations and violations for thermal limits of lies respectively the limits on the control variables transforms to form a pseudo objective function (F)

$$\min F = F_T\left(P_g\right) + P_s + \sum_{i=1}^{NPQ} P_{Vi} + \sum_{i=1}^{NG} P_{Qi} + \sum_{i=1}^{NL} P_{Li} \qquad (16)$$

III. HYBRID BAT ALGORITHM WITH DIFFERENTIAL EVOLUTION STRATEGY

A novel hybrid Bat Algorithm (BA) with the Differential Evolution (DE) strategy using the feasibility-based rules, namely BADE is proposed to deal with the constrained optimization problems. The sound interferences induced by other things are inevitable for the bats which rely on the echolocation to detect and localize the things. Through integration of the DE strategy with BA, the insects' interferences for the bats can be effectively mimicked by BADE. Moreover, the bats swarm' mean velocity is simulated as the other bats' effects on each bat. Bats use echolocation to detect prey and discriminate different types of insects even in the dark. Hence bats are sensitive to the sounds. Bats usually feed on insects, which can emit sound. In a specific habitat, there exist a group of bats, some of which may simultaneously forage for food. Thus bats may be subjected to the noise and interference induced by their prey and their partners.

Through integration of the mutation operator in the DE/rand/1/bin scheme with the BA, the insects‟ interferences for the bats can be visually simulated as a stochastic decision. The insects‟ interferences for the bats only exists when rand (0, 1), a uniform random number in [0, 1], is smaller than CR. Here

CR is the crossover rate in DE. Consider three different individuals interfere with the virtual bats. If the interference is strong enough that the virtual bats cannot distinguish the targets by themselves, they will follow the clues suggested by the interference. Otherwise, they will continue searching for their targets using their own strategies.

Using these criteria, the virtual bats in the proposed algorithm can be more lifelike than the ones in basic BA, thus helping them escape from the local optima.

3.1: ALGORITHM:

The main procedure of the BADE can be described as follows.

Step 1: Initialization

Step 1.1: Initialize *N bats* positionsx_i, velocities $v_i(i\epsilon[1,\dots,N])$ in a *D*-dimensional space, and initialize the associated parameters, such as frequencyf_i, pulse ratesr_i , and the loudnessA_i .

Step 1.2: Evaluate the fitness value of each bat by the objective function $f(x)$ and the constraint value of each bat by the constrained functions.

Step 2: Update solutions.

While *t* < Max number of iterations (*M*)
Step 2.1: Generate offspring (solutions) x_i^{t+1} using the equations

$$f_i = f_{min} + (f_{max} - f_{min})\times\beta \qquad (1)$$

$$v_i^{t+1} = W\times(v_i^t - W_2\times\bar{v}) + (x_i^t - x_*)\times f_i \qquad (2)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1} \qquad (3)$$

Step 2.2: If $(rand(0,1) < r_i)$

Select a solution among the best solutions
Generate a local solution x_i^{t+1} around the selected best solution using the equation

$$x_{new} = x_{old} + \epsilon * A^t \qquad (4)$$

End if
Evaluate the fitness values and constraint values of the offspring x_i^{t+1}.
Step 2.3: If $(rand(0,1) < CR)$
Generate offspring $x_i^{t+1'}$ using the equation

$$\overrightarrow{v_l^{t+1}} = \overrightarrow{x_a^t} + F\left(\overrightarrow{x_b^t} - \overrightarrow{x_c^t}\right) \qquad (5)$$

Evaluate the fitness values and constraint values of the new offspring $x_i^{t+1'}$.

Select the final offspring x_i^{t+1} by comparing the fitness value and constraint value of x_i^{t+1} with those of $x_i^{t+1'}$ according to the feasibility-based rules.
End if

Step 2.4: If $(rand(0,1) < A_i)$
If x_i^t is infeasible, but x_i^{t+1} is feasible
Or both x_i^t, x_i^{t+1} are feasible, but $f(x_i^t) > f(x_i^{t+1})$
Or both x_i^t, x_i^{t+1} are infeasible, but constraint value of x_i^t is bigger than x_i^{t+1} Accept the offspring x_i^{t+1} as the new solutions.
Increase r_i and reduce A_i using the equations

$$A_i^{t+1} = \alpha A_i^t \qquad (6)$$

$$r_i^{t+1} = r_i^0(1 - e^{-\gamma t}) \qquad (7)$$

End if

Step 2.5: Rank the bats and find the current best x_*.

Step2.6: If x_* does not improve in *G* generations.
Reinitialize the loudness A_i, and set the pulse rates r_i , which is uniform random number between [0.85, 0.9].

t=*t*+1. (8)
End while

Step 3: Update the best x_*.

IV. IMPLEMENTATION OF BADE ALGORITHM

BADE algorithm is applied for various optimization problems. It is more convenient for OPF minimization problems. This require a fast and robust load flow program with best convergence properties thus the developed load flow process uses the full Newton Raphson method.

BADE algorithm involves the steps shown below in power flow control

Step 1: Form an initial generation of NP bats in a random manner respecting the limits of search space. Each swarm is a vector of all control variables, i.e. [Pg, Vg,Ttap, Qsh]. There are 5 Pg’s, 6Vg’s, 9Qsh’s and 4 Tk’s in the IEEE-30 system and hence a bat is a vector of size 1X15.

Step 2: Calculate the position, loudness and pulse rate values of all bats solution by running the NR load flow. The control variable values taken by different bats are incorporated in the system data and load flow is run. The total line loss corresponding to different bats are calculated.

Step 3: Determine the best solution after check the feasibility conditions. The bats are arranged in the rank order and the first bat will be the candidate with best solution (minimum cost).

Step 4: Generate new solution around the global best bat solution by adding/subtracting a normal random number. It should be ensured that the control variables are within their limits otherwise adjust the values.

Step 5: Repeat steps by increasing t=t+1 until the best solutions has been achieved.

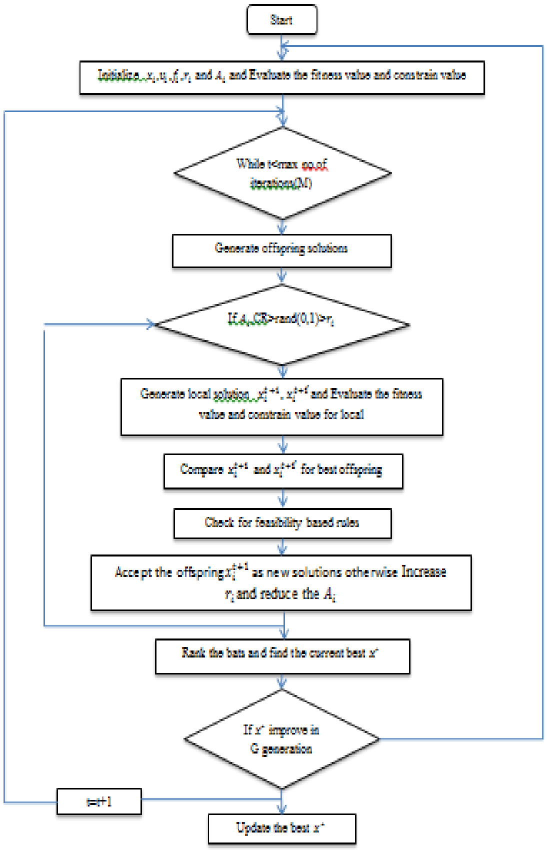

Figure 1: flowchart of bade algorithm

V. NUMERICAL RESULTS AND DISCUSSIONS

The effectiveness of the proposed optimization method is tested on the standard IEEE-30 bus system. The necessary data of the system is taken from [13]. The dimension of this problem is 12 including 6 generator voltages, 4 transformer tap settings and 2 VAR compensators. The first bus is the slack bus and its real power generation is not controlled for OPF. System total load is considered(2.834pu+j1.2620pu) on 100 MVA basis.

5.1 IEEE 30 BUS SYSTEM

The performance of the proposed BADE algorithm based fuel cost optimization method is tested in the standard IEEE-30 bus test system. The line and bus data of the test system are taken from power system test case.

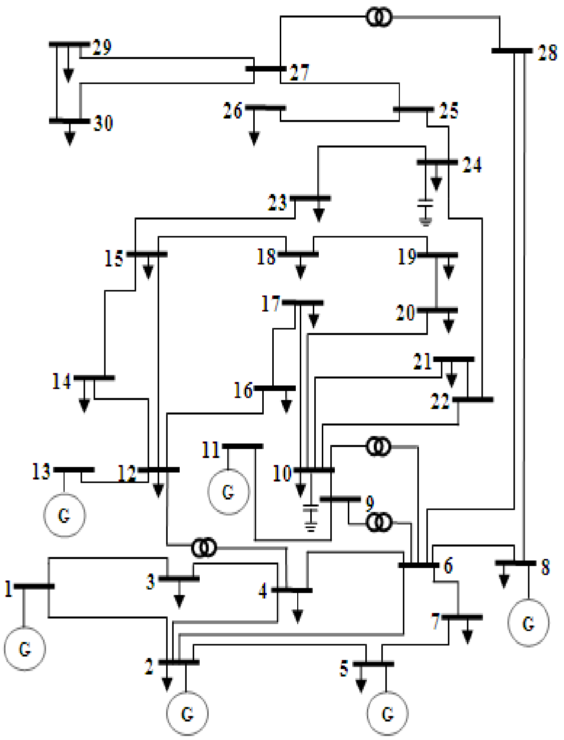

Figure 2: One line diagram of IEEE 30 bus system

The various parameters of the IEEE-30 bus was mentioned in the table 1

Table 1: Parameters of the IEEE-30 bus system

Sl.No.	Parameter	30-bus system
1	Buses	30
2	Branches	41
3	Generator Buses	6
4	Shunt capacitors	2
5	Tap-Changing transformers	4

Quadratic cost function is used for calculating the total fuel cost. The real power generation limits and three cost coefficients are given in table 2. By real power output and cost coefficients the fuel cost of the thermal plant is determined.

Table 2: Real power limits and cost coefficients of generators

Bus No	Real power output limit (MW)		Cost Coefficients		
	Min	Max	A	B	C
1	50	200	0	2.00	0.00375
2	20	80	0	1.75	0.01750
5	15	50	0	1.00	0.06250
8	10	35	0	3.25	0.00834
11	10	30	0	3.00	0.02500
13	12	40	0	3.00	0.02500

The control parameters are adjusted within their limits and the total fuel cost is minimized then other algorithms in the literature.

OPF for smooth case:

The optimal values of the control variables taken by the proposed algorithm in OPF and its comparison with various algorithms are given in table.3

In order to assess the potential of the proposed algorithm a comparison between the results of fuel cost obtained by the proposed BADE algorithm and those reported in the literature has been carried out.

Table 3: Optimal variables for smooth case OPF

Variables Base	case	FFO [8]	BB-BC[8]	LTLBO[11]	BADE
Pg1(pu)	0.987014	1.765171	1.749672	1.7746	1.8073
Pg2(pu)	0.8	0.487865	0.481406	0.486837	0.480581
Pg5(pu)	0.5	0.214746	0.208195	0.213146	0.224622
Pg8(pu)	0.2	0.216439	0.222772	0.208867	0.192427
Pg11(pu)	0.2	0.11980	0.14110	0.118086	0.100000
Pg13(pu)	0.2	0.120276	0.12000	0.120000	0.120000
Vg1(pu)	1.06	1.085421	1.087797	1.1000	1.1000
Vg2(pu)	1.043	1.066785	1.065492	1.0817	1.0911
Vg5(pu)	1.01	1.034902	1.03551	1.0509	1.0501
Vg8(pu)	0	1.043234	1.04532	1.0555	1.0704
Vg11(pu)	1.082	1.069076	1.063822	1.0826	1.0153
Vg13(pu)	1.071	1.059076	1.010111	1.0574	1.1000
Qsh10(pu)	0.19	0.04	0.04	0.05	0.0050
Qsh12(pu)	0	0.03	0.01	0.05	0.0155
Qsh15(pu)	0	0.02	0.02	0.05	0.0500
Qsh17(pu)	0	0.04	0.02	0.05	0.0050
Qsh20(pu)	0	0.04	0.02	0.04	0.0050
Qsh21(pu)	0	0.04	0.05	0.05	0.0500
Qsh23(pu)	0	0.03	0.04	0.03	0.0364
Qsh24(pu)	0.043	0.03	0.04	0.05	0.0500
Qsh29(pu)	0	0.02	0.02	0.03	0.0050
t1(6-9)	0.978	0.9850	1.0950	1.0461	0.9000
t2(6-10)	0.969	0.9650	0.9600	0.9583	1.1000
t3(4-12)	0.932	0.9900	1.0100	0.9996	1.0336

t4(28-27)	0.968	1.005	1.015	0.9891	0.9620
Total Real power generation(pu)	2.887	2.9243	2.9231	2.9215	2.9250
Cost($/hr)	**900.5211**	**800.6803**	**800.8949**	**799.4369**	**799.2141**

The efficiency of the algorithm is proved by comparing its performance with that of other recently reported algorithms like EP, DE, FFO, LTLBO and BADE. It is obvious from table 4 that the reduction in the total fuel cost is quite encouraging in comparison with others.

All the simulations were performed on a personal computer with 3 GHz Intel Processor and 2 GB of RAM running MATLAB 7.6. Load flow calculations were performed by Newton–Raphson method. The cost obtained by other methods is about 802 USD/hr whereas BADE has achieved 799.21487USD/hr.

Table 4: Total fuel cost obtained by different methods

IEEE-30 bus system	DE [14]	BB-BC [8]	FFO [8]	LTLBO [11]	BADE
Cost	802.230	800.894	800.680	799.4369	799.214

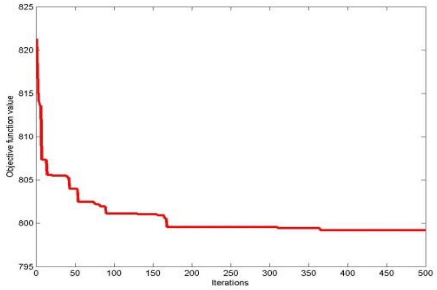

Figure 3: Convergence characteristics of OPF

Convergence efficiency of FOA is good in this case. It is clear from figure 5.2 that convergence occur at about 120th iteration. It is relatively less number of iterations.

OPF for non-smooth case:

In this non-smooth case, we will include loading effect on generating units performance, this is done by adding a sine component to cost curves which simulates valve point loading effects on their characteristics during the Optimal Power Flow problems.

The optimal values of control parameter corresponding to the best results are tabulated in 4. The fuel cost is slightly higher but acceptable as security is more important than economy.

Table 5. Optimal variables for
non-smooth case

Variables Base	LTLBO[11]	BADE
Pg1(pu)	1.9960	2.01057
Pg2(pu)	0.2000	0.20000
Pg5(pu)	0.221234	0.173173
Pg8(pu)	0.250928	0.297141
Pg11(pu)	0.133536	0.134267
Pg13(pu)	0.125664	0.120000
Vg1(pu)	1.1000	1.1000
Vg2(pu)	1.0784	1.0840
Vg5(pu)	1.0492	1.0336
Vg8(pu)	1.0558	1.0465
Vg11(pu)	1.0922	1.0882
Vg13(pu)	1.0642	1.0914
Qsh10(pu)	0.01	0.026679
Qsh12(pu)	0.0	0.044698
Qsh15(pu)	0.03	0.017830
Qsh17(pu)	0.05	0.016541
Qsh20(pu)	0.05	0.005050
Qsh21(pu)	0.05	0.009351
Qsh23(pu)	0.04	0.006019
Qsh24(pu)	0.05	0.015612
Qsh29(pu)	0.03	0.011536
t1(6-9)	1.0431	0.9842
t2(6-10)	0.9599	0.9581
t3(4-12)	0.9979	1.0434
t4(28-27)	0.9897	1.1000

Total Real power generation(pu)	2.92735	2.93515
Cost($/hr)	**917.6259**	**916.4492**

It is clear from figure 4 that convergence occur at about 130th iteration. It is relatively less number of iterations.

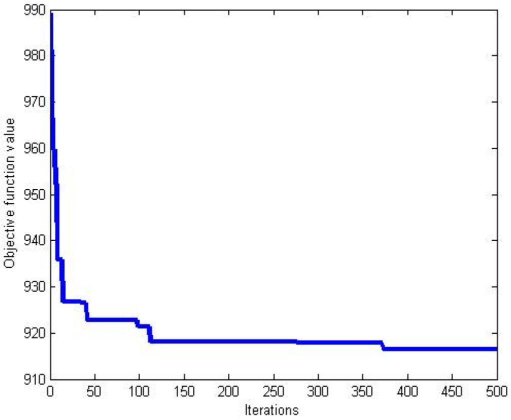

Figure 4: Convergence characteristics for non-smooth OPF

Convergence efficiency of BADE is good in this case also. It is obvious from that the reduction in the total fuel cost is quite encouraging.

VI. CONCLUSION

BADE is new and bio inspired optimization algorithm mimicking the food searching behavior of Bats. Because of less number of operators and parameters, the algorithm is found to be simple in implementation. The proposed algorithm was successfully implemented the goal to find global or near global best settings of the control variables of an IEEE 30-bus. It is obvious from the test results than BADE outperforms the other recently introduced optimization techniques in optimal power flow problem in both smooth and non-smooth case. The algorithm achieves the results in relatively less number of iterations. Speed of convergence of the algorithm is also examined to establish the strength of the algorithm. Therefore it is believed that this algorithm may be exploited for other power system operations like economic load dispatch, optimal power flow, voltage stability improvement etc.

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