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Multi-Objective Optimal Power Flow Problem Using Enhanced Flower Pollination Algorithm

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Abstract

This paper presents an Enhanced flower Pollination Algorithm (EFPA) to solve the optimal power flow (OPF) problem. This paper considers OPF problem with multiple objectives of minimizing generating cost, transmission loss and power plants emission and to improve voltage stability. Generating cost is a function of real power generation of all the generating units. Transmission loss depends on bus voltages and reactive power support in the system. Power plant emission is once again a function of real power and voltage stability is a function of bus voltages and reactive power support. In the optimization problem for real power generation, generator bus voltages, transformer tap positions and injected reactive power support may be considered as control variables. Set of these control variables from a meta-heuristic approach. Enhanced flower pollination strategy may yield a better solution for multi objective problem. This optimization algorithm is compare with other optimization algorithms and the comparison proves the ability of EFPA has given the best results to solve multi objective OPF problem. To evaluate EFPA based multi objective OPF, standard IEEE 30 test case is considered.

1. INTRODUCTION

At present, power systems operation and planning need a solution for the problem of optimal power flow (OPF) which is also called as a problem of an optimization and analysis combination. Economic Load Dispatch (ELD) is one of the major issues to optimize generating cost in power systems operation and planning. Load flow analysis is the most important technique to investigate the problems in power systems where it can provide a balanced steady operation state, without considering system transient processes. To optimize generating cost and load flow estimation of OPF problems by providing secure state of operation using ELD. The scope of power system is to provide stable electricity at low cost. Several traditional optimization techniques have been investigated for mitigating OPF problem to optimize generating cost where power balance and power equation are considered as equality constraint. An equality constraint has been developed with objective function by Lagrangian multiplier [1]. OPF working state should have stability margin for providing secure operation [2]. For solving OPF problems, various traditional techniques such as quadratic programming [3], Newton-based solution of optimality conditions, linear and nonlinear programming, interior point methods hybrid versions of linear and nonlinear programming was investigated [4-6]. These traditional techniques are important to discontinuous, non-convex and prohibited operating zones of OPF problem. To solve these problems intelligent algorithms were used. One of the most popular intelligent algorithm called as genetic algorithm (GA) used to solve OPF problems. GA works based on Darwin's theory of evolution where three major operators such as selection, cross over and mutation were used. For improving the performance of GA, few alterations were made in this algorithm. This altered GA is known as enhanced genetic algorithm which is used to solve OPF problem [7, 8]. This algorithm has good cross-over but feeble mutation. For improving mutation, one more intelligent algorithm called differential evolution (DE) is used for optimization. This algorithm is found to be better to solve both general and stability related OPF problems [9-10]. For solving the issues of complex and non-convex OPF problem using evolutionary algorithm which is capable to solve OPF and multi-objective OPF problems using Pareto-optimal solution [12, 13]. Particle Swarm Optimization (PSO) is the most commonly used population based optimization approach in recent years. The operating principle is based on bird flocking to find global optimal solution where particles position and velocity are essential operators for estimating

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local and global optima and also able to solve multi-objective optimal power flow problems [14]. To improve the performance of PSO approach by an external repository to save all non-dominated solutions while the evolutionary process and a fuzzy decision making method is applied to sort these solutions based on their importance [15]. Further modified differential evolution algorithm for OPF [16] and economic load dispatch for large scale power system using stochastic search algorithms was used [17]. To minimize voltage deviations, multi objective ant colony optimization (ACO) for economic load dispatch of power system with pollution control [18], power losses and control actions in a transmission power system was introduced [19]. By using flower pollination algorithm (FPA), optimal reactive power problem has been solved [20]. To improve the performance FPA, certain modifications are made in this algorithm known as modified flower pollination algorithm (MFPA) for optimal power flow problem [21]. In the recent years, more number of inspired algorithms was developed to solve OPF problem. Differential search algorithm [22], Improved Colliding Bodies Optimization algorithm [23], Glowworm Swarm Optimization [24] are used for solving multi-objective OPF problems. For solving multi-objective OPF problems, more number of optimizations are developed and one among them is an enhanced flower pollination algorithm (EFPA). Operation of EFPA is very simple and it work well for engineering optimization compared with other inspired algorithms for optimizations [25]. In EFPA, for solving multi-objective OPF problem a single objective function has been developed by weighed sum of objective or multi-objective functions. The significance of one objective function may be differentiated from other objective functions based on its weight factor [26]. Also, optimal power flow issue was resolved by meta-heuristic algorithms [27].

The scope of this research is to utilize EFPA efficiently for OPF problem which minimizes generating cost, transmission loss and power plants emission and to improve the voltage stability. Also, equality and inequality constraints are considered. The limits of real and reactive power generation are considered along with other factors like bus voltages, reactive power injections and transformer tap positions.

2. PROBLEM FORMULATION

In this paper, the main objective of OPF problem is to minimize the generating cost where the quadratic equation of cost is developed for comparison purpose. This cost objective function is regarded as the function of real power generation of the distributed generator as expressed in equation (1). Minimization of generating cost is denoted as Fc and it is calculated by following expression,

Generating cost minimization,

$$F_c(y) = \sum_{i=1}^{n_g} (a_i p_{ri}^2 + b_i p_{ri} + c_i) \quad \$/\text{hr} \tag{1}$$

$$y = [p_r, v, t, q_r] \tag{2}$$

$$p_r = [p_{r1}, p_{r2}, ..., p_{rn_g - 1}] \tag{3}$$

$$v = [v_1, v_2, ..., v_{n_g}] \tag{4}$$

$$t = [t_1, t_2, ..., t_{n_t}] \tag{5}$$

$$q_r = [q_{r1}, q_{r2}, ..., q_{rn_c}] \tag{6}$$

$$n_{cv} = ((n_g - 1) + n_g + n_t + n_c) \tag{7}$$

Where,

$F_c(y)$ is generating fuel cost

y is the list of control variables

a_i, b_i, and c_i are quadratic coefficient of fuel cost

p_r is the real power generation

v is voltage magnitude of generator bus

t is transformer tap position

q_r is the reactive power support in the bus

n_g is the number of generator

n_t is the number of transformer

n_c is the number of capacitor or reactive power support

n_{cv} is the number of control variables

Environmental issues of gaseous pollution by thermal power plants are assigned for the social welfare which is included in multi-objective function. The emission minimization objective function (F_e) is used to reduce the gaseous pollution generated at the distributed generator which is the function of real power generation as given in equation (8).

Emission minimization (F_e),

$$F_e(y) = \sum_{j=1}^{n_g} (\alpha_j + \beta_j p_{rj} + \gamma_j P_{rj}^2 + \xi_j e(\lambda_j p_{rj})) \tag{8}$$

Where, α, β, ϒ, λ and ξ are emission coefficients.

Electric power is transmitted from generating station to its consumers through metallic conductors. The conductors have resistance that takes power as heat losses. Reducing these losses in turn reduces the generating cost. This minimization loss (F_l) forms the third objective as expressed in equation (9). The unit of real power loss is MW.

Loss minimization (F_l),

$$F_l(y) = \sum_{j=1}^{n_{br}} g_c [v_t^2 - v_r^2 - 2 v_t v_r \cos(\theta_t - \theta_r)] MW \tag{9}$$

Where,

n_{br} - number of branch or transmission line

g_c - conductance of the conductor

v_t - the sending end bus voltage magnitude

v_r - the receiving end bus voltage magnitude

θ_t and θ_r - sending and receiving end voltage angles

For providing reliable power to the consumers, voltage stability has to be considered. Specifically, voltage stability is an important stability factor for operation of reliable power system and it is measured by L-index. Minimum value of L-index provides maximum stability which is considered as fourth objective function.

L-index minimization given as,

$$L_r = \left| 1 - \sum_{t=1}^{n_g} G_{rt} \frac{v_t}{v_r} \right| \tag{10}$$

The matrix G_{rt} is given in equation (11)

$$[G] = -[Y_{ll}]^{-1} [Y_{\lg}] \tag{11}$$

Where, Y_{ll} is the sub matrix of Y_{bus} for all load buses in the system. The matrix Y_{lg} is the sub matrix of Y_{bus} which corresponds to the generator bus linked to the load buses. The current equation for this admittance matrix is given in equation (12).

$$\boldsymbol{I}_{bus} = \boldsymbol{Y}_{bus} \boldsymbol{V}_{bus} \tag{12}$$

This current equation can be written in sub matrix form as given in the equations (13)-(15),

$$\begin{bmatrix} I_l \\ I_g \end{bmatrix} = \begin{bmatrix} Y_{ll} & Y_{lg} \\ Y_{gl} & Y_{gg} \end{bmatrix} \begin{bmatrix} V_l \\ V_g \end{bmatrix} \tag{13}$$

$$I_l = Y_{ll}.V_l + Y_{lg}.V_g \tag{14}$$

$$Y_{ll}.V_l + Y_{lg}.V_g = 0 \tag{15}$$

From the above equations, it is clear that the load bus voltages are dependent on generator bus voltage and admittance of the line connecting the generator bus to the load bus. The dependency of load bus voltage is given in the following equations (16) and (17).

$$V_l^k = \sum_{i=1}^{n_g} ((Y'_{ll})^{-1}.Y_{lg})_{k,i}.V_g^k \tag{16}$$

$$L_j = \sum_{i=1}^{n_g} ((Y'_{ll}.Y_{lg})_{k,i} \tag{17}$$

The fourth objective function (F_{lm}) is derived from the L-index is given in equation (18).

$$F_{lm}(y) = L = \max(L_j) \tag{18}$$

This multi-objective OPF problem is subjected to constraints on control and dependent variables. These constraints are divided into equality and inequality constraints.

2.1. Equality constraints

Power balance equation for OPF issue provides equality constraint as expressed in equations (19) and (20). Equations (19) and (20) represent the equality constraint for real power and the equality constraints for reactive power respectively.

$$\sum_{i=1}^{n_g} p_G = p_D + p_L \tag{19}$$

$$\sum_{i=1}^{n_g} q_G = q_D + q_L \tag{20}$$

2.2. Inequality constraints

Limits on depended and control variable are derived from an inequality constraint. Control variable p_r has its minimum and maximum limit for power generation which is expressed in equation (21). Control variable, reactive power generation q_r has its minimum and maximum limit for inequality constraint as expressed in equation (22). Similarly, minimum and maximum limits on bus voltage magnitude, transformer tap positions, Mega Volt Amp (MVA) limits of transmission line and capacitor or reactive power support on the bus form inequality constraints are expressed in equation

(23) to (26).

$$p_{ri}^{\min} \le p_{ri} \le p_{ri}^{\max} \quad \text{for, } i = 1 \text{ to } n_g \tag{21}$$

$$q_{ri}^{\min} \le q_{ri} \le q_{ri}^{\max} \quad \text{for, } i = 1 \text{ to } n_g \tag{22}$$

$$v_i^{\min} \le v_i \le v_i^{\max} \quad \text{for, } i = 1 \text{ to } n_b \tag{23}$$

$$t_i^{\min} \le t_i \le t_i^{\max} \quad \text{for, } i = 1 \text{ to } n_t \tag{24}$$

$$MVA_i \leq MVA_i^{\max} \qquad \text{for, } i = 1 \text{ to } n_{br} \tag{25}$$

$$q_{Ci}^{\min} \leq q_{Ci} \leq q_{Ci}^{\max} \qquad \text{for, } i = 1 \text{ to } n_c \tag{26}$$

3. ENHANCED FLOWER POLLINATION ALGORITHM (EFPA)

A set of iterative formulae are derived for implementing EFPA algorithm. In global pollination step, enhanced flower pollen gametes are achieved by pollinators like insects over longer distances. Therefore, the mathematical equivalent of enhanced flower constancy is expressed as,

$$y_i^{t+1} = y_i^t + \gamma L(\lambda)(y_i^t - y_*) \tag{27}$$

Where, y_i^{t+1} is the solution vector (pollen) y_i^t at iteration t, y_* is the current efficient solution, γ is a scaling factor for controlling the step size. $L(\lambda)$ is the parameter that corresponds to the pollination strength, λ is the step size. Since, insects may move over a long distance with different step distances, we can use a Levy flight to mimic this properties effectively. That is, we draw $L > 0$ from a Levy distribution. For local pollination the following formula is used,

$$y_i^{t+1} = y_i^t + \varepsilon(y_i^t - y_k^t) \tag{28}$$

Where, y_j^t and y_k^t are pollen from different enhanced flowers of the same plant species. This essentially mimics enhanced flower constancy in a limited neighbourhood. Mathematically, if y_j^t and y_k^t come from the same species and they are selected from the same population which becomes a local random walk if we draw ε from a uniform distribution in [0, 1]. Pollination may occur in an improved flower from the neighbouring enhanced flowers than the far away enhanced flowers. In order to replicate this, a switch probability is used with a proximity probability p to switch between global and local pollination. A primary parametric shown that p'=0.8 might work better for most of the applications.

3.2. EFPA based multi-objective OPF

The objectives of OPF include generating cost, emission, transmission losses and voltage stability index. This multi-objective issue is solved by using novel Enhanced Flower Pollination Algorithm (EFPA). A set of control variables is formed and the formulation with multi-objective OPF is solved using EFPA along with 15 control variables [15]. In this, first 5 control variables are regarded as real power generators other than slack bus generator, next 6 control variables are bus voltage magnitudes of generator and last 4 control variables are transformer tap settings. Twenty enhanced flowers are considered for the population as given in equation (16).

An enhanced flower in the population undergoes either global or local pollination which is based on switching probability. Total Iterations with one global enhanced flower having best objective function in a particular iteration is developed and an enhanced flower pollinate with this global an enhanced flower for attaining the global pollination. In local pollination, pollination takes place with anyone enhanced flower in the population. This pollination process is repeated for each iterations till it reaches the maximum number of iterations.

Flowchart for multi-objective OPF solution using EFPA is given in Fig.1. For multi-objective function, this algorithm is implemented with maximum of 20 enhanced flowers and 100 iterations are considered.

$$pop = \begin{bmatrix} P_{g2}^{\ 1} & \cdots & P_{g2}^{\ 20} \\ P_{g3}^{\ 1} & \cdots & P_{g3}^{\ 20} \\ P_{g4}^{\ 1} & \cdots & P_{g4}^{\ 20} \\ P_{g5}^{\ 1} & \cdots & P_{g5}^{\ 20} \\ P_{g6}^{\ 1} & \cdots & P_{g6}^{\ 20} \\ V_{g1}^{\ 1} & \cdots & V_{g1}^{\ 20} \\ V_{g2}^{\ 1} & \cdots & V_{g2}^{\ 20} \\ V_{g3}^{\ 1} & \cdots & V_{g3}^{\ 20} \\ V_{g4}^{\ 1} & \cdots & V_{g5}^{\ 20} \\ V_{g5}^{\ 1} & \cdots & V_{g5}^{\ 20} \\ V_{g6}^{\ 1} & \cdots & V_{g6}^{\ 20} \\ T_1^1 & \cdots & T_1^{20} \\ T_2^1 & \cdots & T_2^{20} \\ T_3^1 & \cdots & T_3^{20} \\ T_4^1 & \cdots & T_4^{20} \end{bmatrix} \tag{29}$$

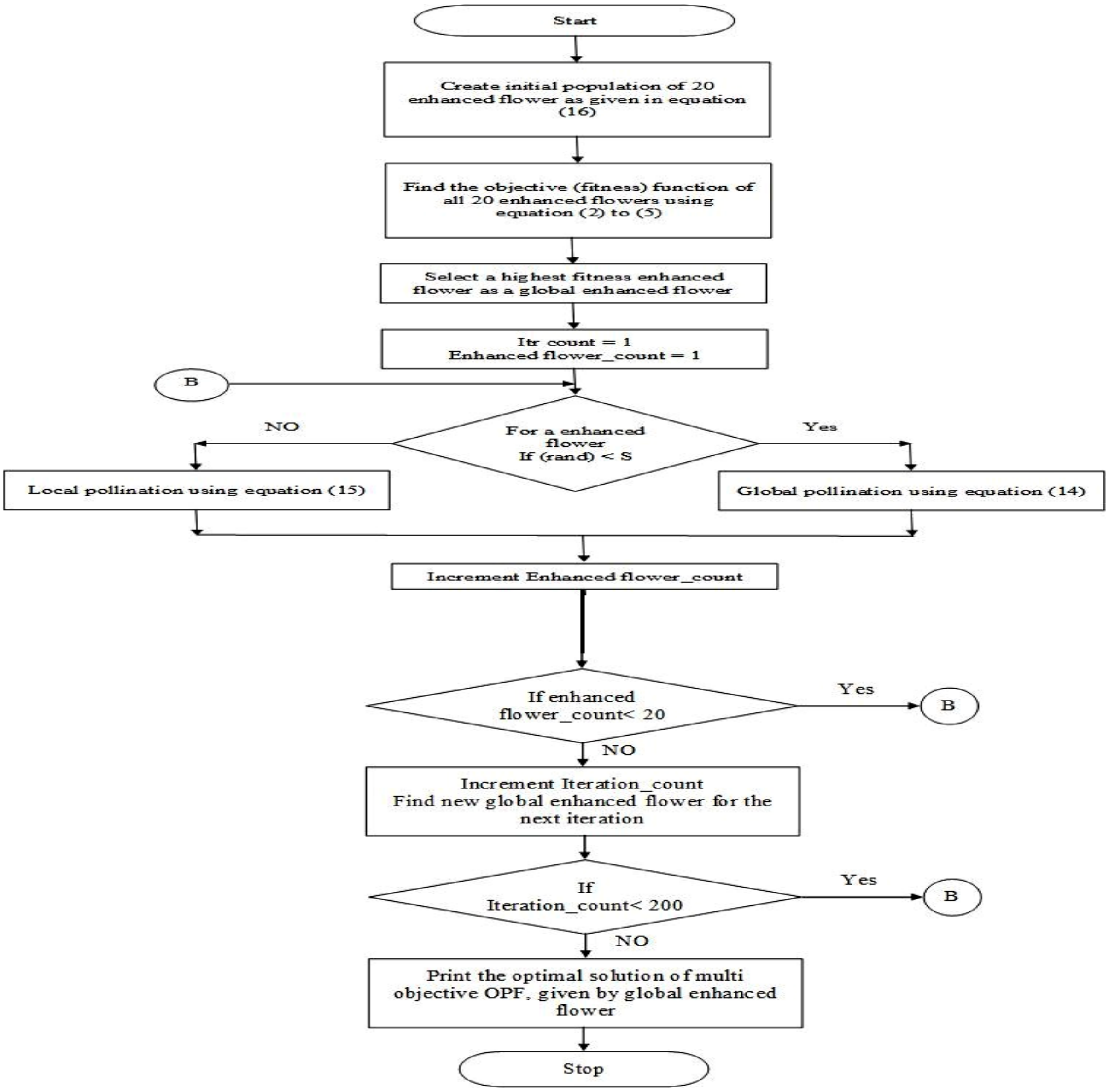

Figure 1. *EFPA flowchart for OPF problem*

4.RESULTS & DISCUSSION

The performance evaluation of developed algorithms with bench mark test case IEEE 30 bus system shown in Fig 2. In these paper Numerical outcomes of IEEE 30 bus is presented and discussed. It has 6 generators include slack bus, 6 generator bus voltage magnitude, 5-real power generation and 4 transformer tap position were considered as control variables with base MVA of the system is 100MVA.

For the test case, generation cost and emission coefficients are given in Table 1. It has the system has 6 generators and its corresponding coefficients were listed. In this operation four objectives were considered. The analysis is performed in MATLAB R2015 software. The system configuration is windows 10, core i5 processor, 8gb RAM.

Table 2 depicted a comparison cost obtained by various optimization methods. The scheduling of generators and associated cost were compared with 8 recent methods and was found that EFPA provided minimum cost. The convergence curve obtained for cost minimization objective was shown in Fig.3.

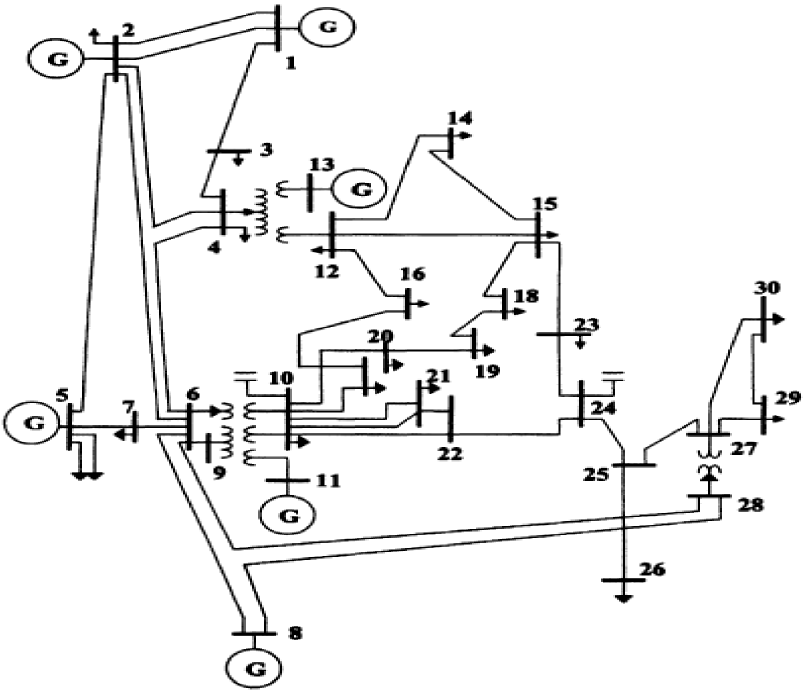

Figure 2. *Single line diagram of IEEE 30 bus system*

Table 1. *Test case IEEE 30 bus systems cost and emission coefficients*

Cost coefficients						
	G1	G2	G3	G4	G5	G6
a	0.0375	0.0175	0.0625	0.00834	0.025	0.025
b	2	1.75	1	3.25	3	3
c	0	0	0	0	0	0
Emission coefficients						
ϒ	0.06490	0.05638	0.04586	0.03380	0.04586	0.05151
β	-0.5554	-0.06047	-0.05094	-0.03550	-0.05094	-0.05555
α	0.04091	0.02543	0.04258	0.05326	0.04258	0.06131
ξ	0.0002	0.0005	0.000001	0.002	0.000001	0.00001
λ	2.857	3.333	8.00	2.00	8.00	6.667

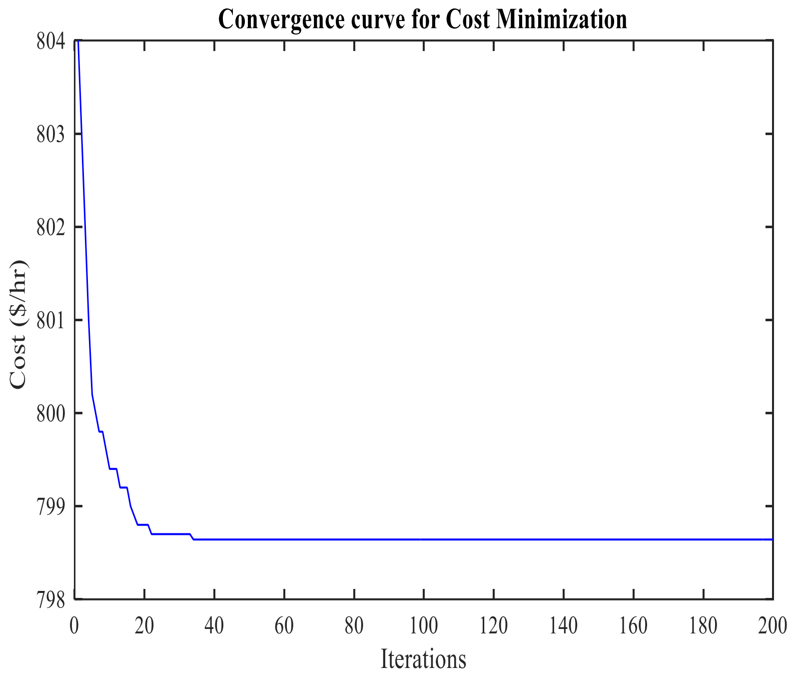

Figure 3. *Convergence characteristic of EFPA for cost minimization objective*

Table 2. *Cost minimization objective*

Gen	**MDE[16]**	**SGA[17]**	**ACO[18]**	**PSO[15]**	**IPSO[15]**	**DSA[22]**	**ICBO[23]**	**GSO[24]**	**EFPA**
Pg1	176.009	175.974	181.945	178.4646	177.0431	176.954	177.0420	174.92	176.2321
Pg2	48.801	48.884	47.001	46.274	49.209	48.713	48.6983	44.15	48.7936
Pg3	21.334	21.51	20.553	21.4596	21.5135	21.383	21.3264	21.76	21.4060
Pg4	22.262	22.24	21.146	21.446	22.648	21.285	21.0768	25.73	21.40
Pg5	12.46	12.251	10.433	13.207	10.4146	12.044	11.8689	11.12	12.0123
Pg6	12	12	12.173	12.0134	12	12	12.0008	13.81	12
Cost ($/hr)	802.376	803.699	802.578	802.205	801.978	800.3887	799.0353	799.06	**798.6421**
Loss	9.466	9.459	9.851	9.4646	9.4282	8.989	8.6132	8.09	8.444

Table 3*. Loss minimization objective*

Variables	Base case [19]	SPEA [19]	GA [19]	PSO [15]	IPSO [15]	DSA [22]	**EFPA**
Vg1	1.05	1.05	1.03	1.045	1.047	1.0605	1.0912
Vg2	1.045	1.044	1.03	1.043	1.044	1.0566	1.0891
Vg3	1.01	1.023	1.00	0.998	0.976	1.0378	1.0631
Vg4	1.01	1.022	1.00	1.009	1.035	1.0453	1.0828
Vg5	1.05	1.043	1.02	1.014	0.984	1.100	1.0410
Vg6	1.05	1.043	1.04	1.047	1.042	1.0474	1.0829
T1	0.97	1.09	1.00	1.012	1.029	1.0329	0.9875
T2	0.96	0.90	1.01	0.971	0.98	0.9993	0.9951
T3	0.93	1.02	1.00	1.023	1.01	0.9913	1.0305
T4	0.96	0.96	1.04	1.014	0.97	0.9786	1.046
Loss (MW)	5.4356	5.199	5.3513	5.2105	5.0732	**3.094**	**3.060**

In Table 3, the objective function considered was loss where the algorithm outperforms by producing a better result compared to 6 other existing methods. The power loss obtained during the method was 3.06 MW which was considerably low.

Here, the voltage profile was also under the desired limits. The convergence curve for power loss minimization objective was shown in Fig 4. It was clear from that EFPA converges in less than 20 iterations.

Stability index of voltage is an essential problem in stability point of view. For quality supply of an electric power the voltage has to be maintained within the tolerance. Voltage stability index of all algorithms were compared in table 4.

Table 4. *Voltage stability index objective*

Control Variables	Initial[19]	EGA[19]	PSO[15]	**DSA[22]**	**CADE[27]**	**EFPA**
Vg1	1	1.0618	1.0493	1.067	1.0965	1.005
Vg2	1	1.053	1.0485	1.0725	1.0994	0.991
Vg3	1	1.053	1.049	1.060	1.007	1.016
Vg4	1	1.014	1.026	1.05	1.0982	0.992
Vg5	1	1.025	1.025	1.057	1.0988	1.055
Vg6	1	1.046	1.031	1.0107	1.0765	1.010
T1	1	0.9125	0.98	1.05	0.9125	0.923
T2	1	0.9	0.92	0.9	0.925	1.028

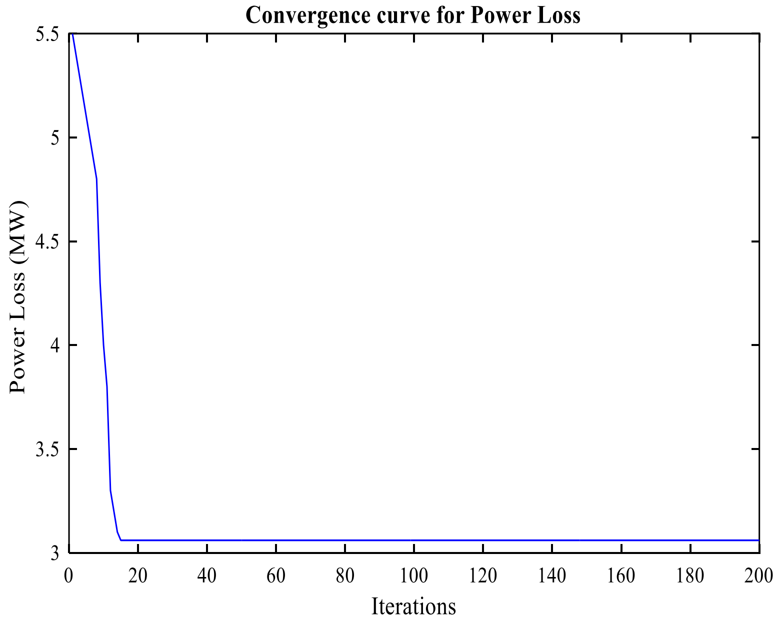

Figure 4. *Convergence characteristic of EFPA for loss minimization objective*

Table 5. *Emission minimization objective*

Gen	**GA [19]**	**PSO [15]**	**IPSO [15]**	**DSA [22]**	**EFPA**
Pg1	69.73	67.13	67.04	64.0725	63.8795
Pg2	67.84	68.94	68.14	67.5711	68.1400
Pg3	49.73	49.73	50	50	50.0000
Pg4	34.42	34.42	35	35	35.0000
Pg5	29.15	29.67	30	30	30.0000

Pg6	39.29	39.29	40	40	40.0000
Emission (ton/hr)	0.20723	0.2063	0.2060	**0.20582**	**0.2057**

EFPA gives minimum voltage stability **0.0877** as compared to all other existing algorithms. The converge curve for VSI was shown in Fig 5, from which it could be inferred that VSI was obtained in less than 18 iterations. Comparison of various optimization results was shown in Fig 6.

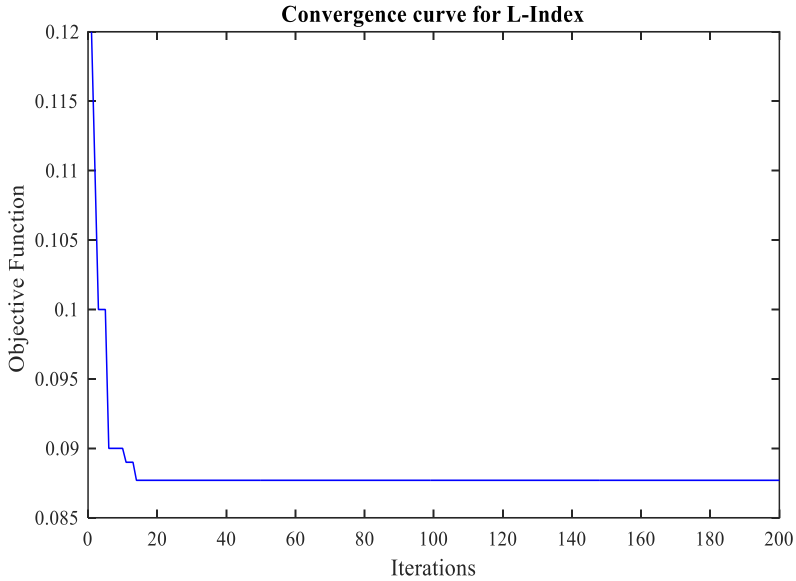

Figure 5. *Convergence characteristic of L-index*

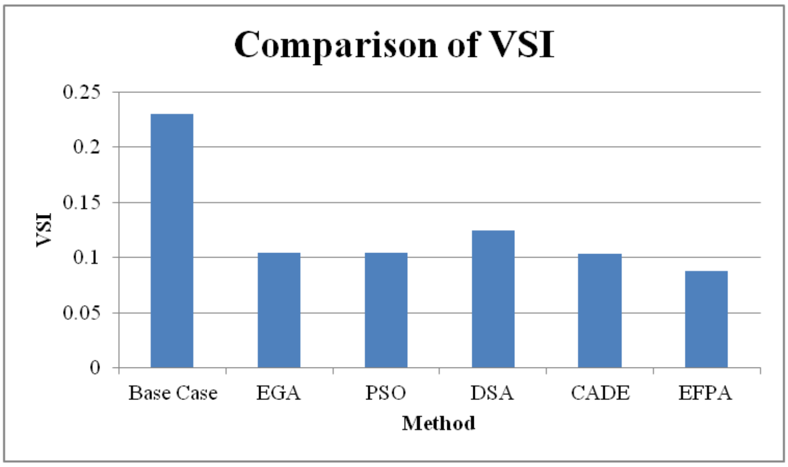

Figure 6. *Comparison of VSI minimization with various algorithms*

Global warming is an important problem for the social welfare and to leave undamaged nature for our next generation. This global warming is increased due to emission CO and CO_2 which are produced after the brunt of coal for electric power generation. So, this emission has to be reduced as far as possible. For the test case, emission was estimated for all algorithms and given in Table 5.

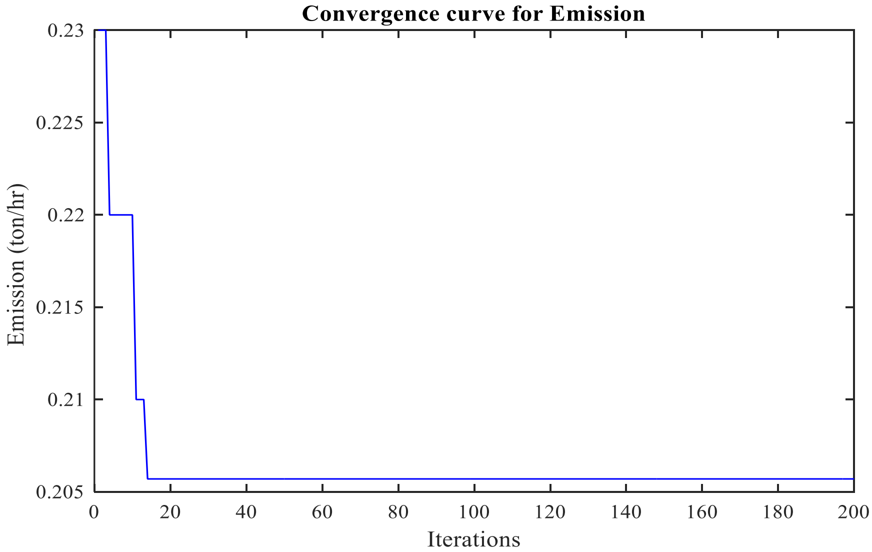

Figure 7. *Convergence characteristic of EFPA for emission minimization objective*

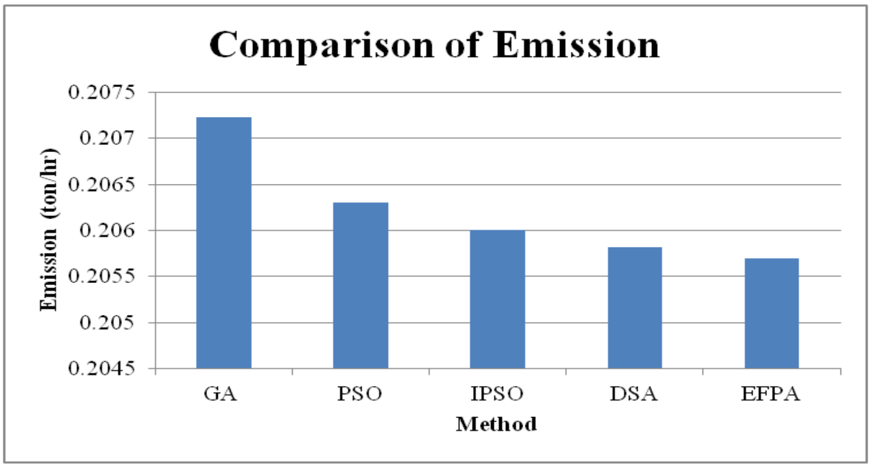

Figure 8. *Comparison of emission minimization with various algorithms*

From the table 5 EFPA gives minimum emission as **0.2057** ton/hr as compared to all other existing algorithms. The generator scheduling for emission minimization was also given in the Table 5. The emission minimization objective convergence curve was shown in Fig 7. The comparison of various optimization algorithms was shown in Fig 8.

5.CONCLUSION

This paper compares many intelligent algorithms and used new optimization algorithm EFPA to solve multi-objective OPF. This optimization algorithm gives minimum objective solution as compared to other algorithms. The multi objective solution as given in the paper satisfied control and depended variables limit and considered social welfare by minimizing emission of the power plants. The quality of the power was improved by enhancing VSI. For providing best price to the consumption the cost is optimized by EFPA. Minimization of loss gave improvement in transmission system and helps to the firm and consumer in term of cost. EFPA gave better global Pareto solution as compared to other algorithm and suitable for OPF optimization problem. For the future work EFPA may use to solve dynamic OPF, which calculates OPF solution for 24 hours in a day. This dynamic OPF is helpful for real time implementation for the algorithm. For a practical case OPF, renewable energy sources like wind and solar energy may be included in the power system data to find best optimal solution.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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