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SOLVING MULTI-OBJECTIVE OPTIMAL POWER FLOW USING MULTI-OBJECTIVE ELECTRO SEARCH ALGORITHM

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Abstract- In this paper Multi-Objective Electro Search algorithm (MOES) is presented for solving optimal power flow (OPF) in electric power networks. This paper solves OPF problem in order to optimize fuel cost, active power loss and emission. This research, utilizes crowding distance computations and non-dominated sorting method to obtain non-dominated optimal solutions. This paper uses fuzzy based determination method in order to choose the proper solution from the non-dominated optimal set of solutions. IEEE 30-bus test network is used to evaluate performance of MOES algorithm for optimizing power flow in the networks.

Keywords: Optimal Power Flow, Multi-Objective Optimal Power Flow, Electro Search Algorithm, Multi-Objective Electro Search Algorithm.

I. INTRODUCTION

OPF problem is a necessary optimization issues in power networks which minimizes fuel cost and many other objectives i.e. active power loss as supplying loads and complying important operative constraints [1, 2]. In most of optimization issues in reality i.e. OPF it is important to comply several goals, simultaneously. In most of the real optimization issues, the optimal solutions of different objectives are not equal. Because imply several goals together, set of solutions must obtained instead of single solution as best solution. The optimal solution of the multi objective optimization problems is set of optimal solutions called non-dominated Pareto optimal solutions. One of these optimal solutions can be used as optimal solution which is chosen using decision making methods [3].

OPF problem is a non-linear, non-convex and highly bound optimization problem with several incomparable goals. Many different methods which has been used to solve single objective OPF is as follows: linear (LP) and non-linear programming (NLP) [4, 5], quadratic programming (QP) [6], interior point method and newton method [7, 8]. In order to meet 2 incomparable goals in OPF problem, it should be solved as a multi-objective optimizing issue.

MO problem has special methods. Weighting factor method is a method of solving which change the multi-objective problem to a single objective problem. Weighting factor method needs lots of program runs with different weighting factors to get the non-dominated optimal solutions [8]. Another method of solving MO problems is ε-constraint method. This method selects the most important objective as the objective function and converts other objectives to constraints in the limit ε [9].

Goal attainment method is another method of solving MO optimization issues [10]. Usual optimization methods convert multi-objective problem to a one objective problem using certain methods. Using these methods require high program number of runs in order to obtain Pareto front.

Lately, researchers have proposed many methods to overcome these limitations. These methods use meta-heuristic algorithms such as: particle swarm optimization (PSO) [12], genetic algorithm (GA) [11], gravitational search algorithm (GSA) [15], harmony search (HS) [14], differential evolution (DE) algorithm [13] and modified shuffle frog leaping algorithm (MSFLA) [16, 17] which have used to handle MO-OPF problem.

Electro Search (ES) algorithm is a new optimizing algorithm inspired from nature based on the spinning of electrons around the nucleus of an atom [18]. Electro search (ES) algorithm utilizes physical principals such as Bohr model and Rydberg formula in solution searching method. In this approach, ES algorithm is utilized to solve one objective optimal power flow and non-dominated sorting method and crowding distance computations are used to solve multi objective OPF by ES algorithm. Multi-objective ES uses crowding distance calculation and non-dominated sorting method to get non-dominated optimal solutions.

Rest of the paper is formed as below: Section II, presents formulation of the MO-OPF problem. Section III, discusses the method of comparing solutions in problems with more than one objectives and procedure of using fuzzy method for selecting optimal solution among Pareto set. In section IV, a summery overview on electro search algorithm is provided. In section V, accomplishment of MO-OPF by ES algorithm is described. Section VI, presents simulation results and Section VII presents the conclusion.

II. PROBLEM FORMULATION

Optimal power flow is a nonlinear, non-convex and complicated optimizing problem in power systems. The aim of optimal power flow is to find all of the controlling variables which find minimum of objective functions (i.e. fuel cost) and meet constraints.

A. Fuel Cost Function

Total fuel cost of system can be simulated using a second-class function as follows:

$$F_1(P_{gi}) = \sum_{i=1}^{N_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \quad (1)$$

where, $F_1(P_{gi})$ is cost of fuel consumed in *i*th generator (\$/h), N_g is generators number, P_{gi} (MW) refers to the MW of energy generated by the *i*th generator and a_i, b_i, c_i refer to coefficients of cost function of *i*th generator, respectively.

B. Emission Function

Generation units which use oil release pollutant gasses i.e. SO_X and NO_X as polluting gasses. Emission released from all generators of system, could be expressed as following formula:

$$F_2(P_{gi}) = \sum_{i=1}^{N_g} (\alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \varepsilon_i \exp(\lambda_i P_{gi})) \quad (2)$$

where, $F_2(P_{gi})$ is released emission from *i*th generator (ton/h) and $\alpha_i, \beta_i, \gamma_i, \varepsilon_i, \lambda_i$ are coefficients of *i*th generator in emission cost function.

C. Active Power Loss Function

Active power loss of whole network could be calculated using following formula:

$$P_{loss} = \sum_{k=1}^{N_l} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \quad (3)$$

where, $(V_i, \theta_i), (V_j, \theta_j)$ are voltage altitude and angles of buses *i* and *j*, respectively and g_k is conductance of the line connecting the buses *i* and *j*.

D. Control Variables

The control variables are as follows:

$$X = [P_g, V_g, T, Q_c]_{1\times N} \quad (4)$$

$$P_g = [P_{g1}, P_{g2}, \ldots, P_{g(N_g-1)}]_{1\times(N_g-1)} \quad (5)$$

$$V_g = [V_{g1}, V_{g2}, \ldots, V_{gN_g}]_{1\times N_g} \quad (6)$$

$$T = [T_1, T_2, \ldots, T_{N_t}]_{1\times N_t} \quad (7)$$

$$Q_c = [Q_{c1}, Q_{c2}, \ldots, Q_{cN_c}]_{1\times N_c} \quad (8)$$

where, vector X refers to decision variables vector including active power of generators besides slack generator (P_g), V_g refers to voltage altitude of generating buses, T refers to tap of tap transformers and Q_c refers to the reactive power injected by capacitors.

E. Equality Constraints

The equality constraints of optimal power flow problem are power flow equations which are non-linear equations that can be expressed as follows:

$$P_{gi} - P_{di} = \sum_{j=1}^{N_b} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad (9)$$

$$Q_{gi} - Q_{di} = \sum_{j=1}^{N_b} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \quad (10)$$

For all busses of the network, these constraints must be elapsed. In these equations, P_{gi} and Q_{gi} are output active and reactive power of generators, P_{di} and Q_{di} are active and reactive power load at the *i*th bus, respectively, N_b is the buses number, and $(V_i, \theta_i), (V_j, \theta_j)$ are the voltage altitude and angle at the *i*th and *j*th buses and $\theta_{ij} = \theta_i - \theta_j$.

F. Inequality Constraints

Control and output variables of optimal power flow problem due to some operational and system limitations should not exceed their allowable range. These limitations are known as inequality constraints of OPF.

- Constraints of generation units:

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}, \; i = 1, 2, \ldots, N_g \quad (11)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}, \; i = 1, 2, \ldots, N_g \quad (12)$$

$$V_{gi}^{\min} \le V_{gi} \le V_{gi}^{\max}, \; i = 1, 2, \ldots, N_g \quad (13)$$

- Tap of Transformers constraint:

$$T_i^{\min} \le T_i \le T_i^{\max}, \; i = 1, 2, \ldots, N_t \quad (14)$$

- Shunt VAR injection:

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max}, \; i = 1, 2, \ldots, N_c \quad (15)$$

- Security constraints:

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max}, \; i = 1, 2, \ldots, N_{pq} \quad (16)$$

$$|S_{ij}| \le S_{ij}^{\max}, \; i, j = 1, 2, \ldots, N_l \quad (17)$$

where, N_L, N_{pq} are the connecting branches and *PQ* buses numbers, S_{ij} is power passing the branch which connects bus *i* to bus *j*, and V_{Li} is the magnitude of voltage of *PQ* buses. It is notable that min and max superscripts refer to lower and upper range of each variable.

III. MULTI-OBJECTIVE OPTIMIZATION

The multi-objective optimizing problem has several competing objectives. The methods which are proposed to solve multi-objective problems should obtain a set of solution that is optimal in due to each objective while passing all equality and inequality constraints. Multi objective problem could be formulated mathematically as follows:

$$\min \{f_1(x), f_2(x), \ldots, f_m(x)\} \quad (18)$$

$$\text{s.t. } g_j(x) = 0, \; j = 1, 2, \ldots, p \quad (19)$$

$$h_k(x) \le 0, \; k = 1, 2, \ldots, q \quad (20)$$

where, f_i refers to ith objective function, $g_j(x)$ and $h_k(x)$ are equality and inequality constraints. In proposed method two steps are used to solve multi objective problem as follows:
(a) Finding the set of optimal solutions called non-dominated optimal solutions (Pareto solutions).
(b) Choosing proper solution among Pareto optimal set.

A. Domination Concept

It is obvious that every control set of variables for multi objective problem have more than one fitness values, so the solutions could not be compared by traditional mathematical methods. In this situation, solution vectors can be compared using domination method. Consider X_1 and X_2 are two variant solution vectors of the multi objective problem. The X_1 is better solution if it can dominate X_2. Domination is mathematically as follows:

$$\begin{cases} \forall i \in \{1,2,\dots,m\}, & F_i(X_1) \le F_i(X_2) \\ \exists j \in \{1,2,\dots,m\}, & F_j(X_1) < F_j(X_2) \end{cases} \tag{21}$$

B. Fuzzy Method for Making Decision

As mentioned, it is important to select a solution among the solutions of non-dominated optimal set of solutions as optimal solution. In this regard, fuzzy decision making method is utilized in this paper. For this reason, a fuzzy membership value is determined to each solution according to fitness value of each objective function. Solutions with preferable fitness values are imputation a better fuzzy membership value. The fuzzy membership function which is used to determine fuzzy membership value of $F_i(X)$ object function is as following formula:

$$\begin{cases} \mu_i(X) = 1 & , \quad F_i(X) \le F_i^{\min} \\ \dfrac{F_i^{\max} - F_i(X)}{F_i^{\max} - F_i^{\min}} & , \quad F_i^{\min} \le F_i(X) \le F_i^{\max} \\ 0 & , \quad F_i(X) \le F_i^{\max} \end{cases} \tag{22}$$

where, $F_i^{\min}$ and $F_i^{\max}$ are lower and upper values of $F_i(X)$. After determination of fuzzy membership according to each objective function for every solution, the main fuzzy membership value is calculated using following formula:

$$F(X) = \min[\mu_1(X), \dots, \mu_m(X)] \tag{23}$$

The best optimal solution is the solution which has the higher value of $F(X)$ between other solutions.

IV. ELECTRO SEARCH ALGORITHM

Electro Search (SE) algorithm is a new optimization algorithm inspired from nature based on the spinning of electrons around the nucleus of an atom [31]. Electro search (ES) algorithm utilizes physical principals such as Bohr model and Rydberg formula in solution searching method. Electro search algorithm presents three phases for solution searching procedure.

The first phase is spreading phase; the atoms are randomly distributed in the molecular space (spreading the candidate solutions in the search space). The second phase is orbital transition phase in which the electrons go to larger orbits in order to reach higher energy levels (searching for better fitness values). The third phase is relocation phase; the atoms move towards the best location of the whole atoms. The important feature of the ES algorithm is that ES algorithm do not need parameter tuning in the global optimal searching process:

A. Structure of an Atom

Atoms are made of nucleus and one or more electrons orbiting around the nucleus, this is the Bohr's atomic model. The basic feature of the Bohr's atomic model is that the energy of electrons orbiting in the atom are discrete values known as quantized levels. According to Bohr's model only certain radii for orbits are allowed and the orbits between them are not stable. According to quantum mechanics, electrons can transit between the orbits by absorption or emission of the difference energy.

When an electron goes to a large orbit, it may return to the initial orbit by emitting a photon. In hydrogen atom, the energy of the emitted photon can be calculated using Rydberg formula which is as follows:

$$E = E_i - E_f = R_E(1/n_f^2 - 1/n_i^2) \tag{24}$$

where, n_f and n_i are the final and initial orbits, respectively, and R_E is the Rydberg energy. According to $E = hc / \lambda$, wavelength of the emitted photon can be calculated by following expression:

$$1/\lambda = R(1/n_f^2 - 1/n_i^2) \tag{25}$$

where, R is Rydberg constant ($R = R_E / hc$). In the ES algorithm, searching for solutions with better fitness function value is analogous to electrons searching for higher energy levels and the domain of infeasible solutions is analogous to the molecular space that atoms are stated. The electrons spinning the nucleus of each atom change their orbits until obtaining molecular states with highest energy level that is analogous to the global optimal solution.

B. The ES Algorithm Phases

As mentioned, ES algorithm can be introduced in three phases as below:

B.1. Atom Spreading; The First Phase

In this phase, the candidate solutions are randomly spread in the infeasible domain of the problem solutions. Each of the candidate solutions is analogous to an atom. Each atom has electrons which orbit the nucleus. According to Bohr's model the electrons can transit between the orbits by absorbing or emitting photons.

B.2. Atom Spreading; The Second Phase

In this phase, the electrons rotating nucleus go to higher energy levels. The ES algorithm inspired solutions local search from the concept of the quantized energy levels in hydrogen atom. This process can be formulated as following expressions:

$$e_i = N_i + (2\times \text{rand} - 1)(1 - \frac{1}{n^2})r \quad (26)$$

$n \in 2,3,4,5$, $\text{rand} \in [0,1]$

where, N_i is the current position of the nucleus, rand is a random number in the range [0,1] with uniform distribution, n is the energy level and the orbital number in which electrons can rotate, r is the orbital radius defined by using D_k (r is defined randomly in the first iteration). In each iteration, the electrons are located in the orbitals using equation. Then the fitness of electrons is evaluated. The electrons with the best fitness (highest energy) are known as e_{best}. In the next step, e_{best} is used to relocating the nucleus in global searching process.

B.3. Atom Spreading; The Third Phase

In this phase, the nucleus is relocated based on the energy of an emitted photon. The formulated nucleus relocation based on Rydberg formula is as follows:

$$\vec{D}_k = (\vec{e}_{best} - \vec{N}_{best}) + Re_k \otimes (\frac{1}{\vec{N}_{best}^2} - \frac{1}{\vec{N}_k^2}) \quad (27)$$

$$\vec{N}_{new,k} = \vec{N}_k + Ac_k \times \vec{D}_k \quad (28)$$

where, k is iteration number, $\vec{D}_k$ is the relocation distance, $\vec{N}_{best}$ is the current best nucleus position, $\vec{e}_{best}$ refer to the best electron around the nucleus, $\vec{N}_k$ refers to the current position of the nucleus, Re_k is Rydberg's energy constant, Ac_k is accelerator coefficient. Note that presented equations are in vector form and the symbol $\otimes$ denotes element by element vector multiplication. This procedure is performed on all nuclei in order to replace all of the atoms towards the global optimum solution. Detailed information about parameter tuning and about algorithm can be found in [18].

V. MOES ALGORITHM FOR MO-OPF PROBLEM

In this research, each vector of solution is analogous to an atom of the ES algorithm. Active power and voltage of generation units, reactive power injected by capacitors and tap of transformers are control variables in this algorithm. The introduced MOES algorithm that is retrieved from the ES algorithm [18], is as follows:

1. Determine network data including bus, line and load data, coefficient of cost and emission function of generation units and algorithm parameters consisting iteration and atoms number.
2. Spread atoms within the feasible region and generate electrons around each nucleus.
3. Investigate satisfaction of power flow equality constraints (Running Matpower load flow program for every atom).
4. Evaluate the fitness values of nuclei and electrons (fuel cost, emission or loss) and crowding distance for atoms and sort them according to fitness and crowding distance values.
5. For each nucleus set e_{best} and N_{best}.
6. Update the position of each nucleus.
7. Evaluate feasibility of the solutions and Investigate satisfaction of power flow equality constraints
8. Evaluate fitness and crowding distance and sort modified atoms according to them.
9. For each new nucleus set e_{best} and N_{best}.
10. Calculate crowding distance for the new atoms and separate non-dominated solutions.
11. Create set of Pareto front.
12. Go to 6 and repeat rest of steps until stop criteria reach.

VI. SIMULATION RESULTS

In this paper, ES and MOES algorithms are evaluated for solving OPF problem as single objective and multi objective problems on IEEE 30-bus test network. This system has 6 generation units, 4 tap changing transformers and 9 reactive power injecting capacitors. Network data of the IEEE 30-bus network could be reached in [19]. Emission and cost function coefficients for generators of this network can be reached in [20]. Reported results are obtained utilizing 100 atoms and 100 iteration. Matpower 4.1 is utilized for power flow computations.

In this paper, five test cases consist of three test cases for single objective OPF and two cases are defined for multi objective OPF. In all of these test cases, voltage and tap of transformers limit is assumed to vary in the bound of [0.95, 1.1] pu and [0.9, 1.1] pu. Reactive power generated by capacitors can be raised up to 0.05 pu.

A. Single Objective Problem Results

Before utilizing the ES algorithm to solve multi objective optimal power flow, single objective OPF by taking into account variant objectives is solved using ES algorithm. In this regard, performance of the method is evaluated and lower and upper values of each objective function for MO-OPF problem solving are obtained. Single objective optimization of this research consists of three cases; related results and control variables of them are presented in Table 4. This table compares control variables and value of objective functions with results of Artificial Bee Colony algorithm [21]. According to this comparison superiority of ES algorithm in solving single objective OPF problem is obvious.

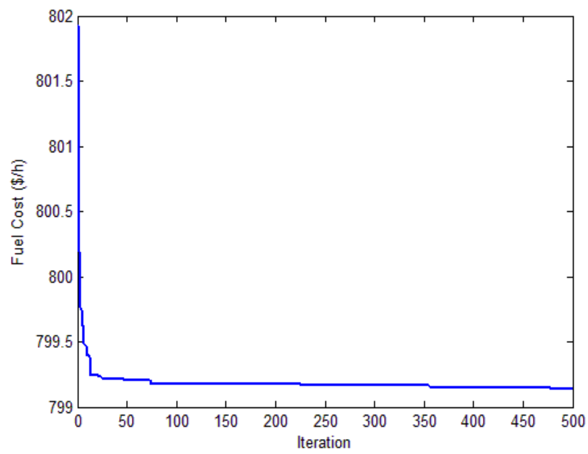

Figure 1. Convergence characteristic of solving OPF with fuel cost minimization (Case 1)

Table 1. Comparison of results for solving OPF with fuel cost minimization (Case 1)

Method	Fuel cost ($/h)
ES	799.129
ABC [21]	800.66
GSA [16]	805.1752
HS[15]	798.8000 [a]
Parallel PSO [22]	800.64 [a]
MSFLA [17]	802.287
EGA [22]	799.56 [a]
DE[14]	799.2891 [a]
MDE[23]	802.376 [a]
PSO[13]	800.41 [a]
EGA[22]	802.06
Gradient method [24]	804.853 [a]
a = Infeasible solution	

A.1. Case 1

Total Fuel cost of generators of network is taken into account as objective of optimal power flow problem, in this case. Minimum fuel cost resulted in this case is tabulated with minimum fuel cost resulted by many other algorithms in Table 1. In this table, it is obvious that fuel cost reached with ES algorithm is less than others. According to Table 1, some of the results have referred as infeasible solutions according to [21]. According to this table and other algorithms reported results, it is considered that minimum fuel cost of ES algorithm is 799.129 $/h, which is 0.19% better than best feasible solution in the table. Convergence characteristic of ES for this case is given in Figure 1.

A.2. Case 2

In this case, objective function of single objective optimal power flow considered to be total power loss in the network. Figure 2 presents convergence characteristic of solution searching process of ES algorithm in this case. Table 2 demonstrates reached result and compare with results reached by ABC algorithm, HS algorithm and EGA. According to [21], result reported in [15], which presents solution of the single objective OPF using HS algorithm, is infeasible. In this case, minimum active power loss reached by employing ES for OPF problem is 2.8542 MW. This result is 8% less than best infeasible result reported in this table.

A.3. Case 3

This case considers released pollutants of generators as objective of single objective OPF problem. Best result reached for solving single objective OPF using ES algorithm is 0.20477 ton/h. This result is 0.003% less than best reported results given in Table 3. Figure 3 presents solution convergence graph of the ES algorithm for Case 3.

Table 2. Comparison of results for solving OPF while power loss minimization (Case 2)

Method	Total power loss (MW)
ES	2.8565
ABC [21]	3.1078
HS [15]	2.9678 [a]
EGA [22]	3.2008
a = Infeasible solution	

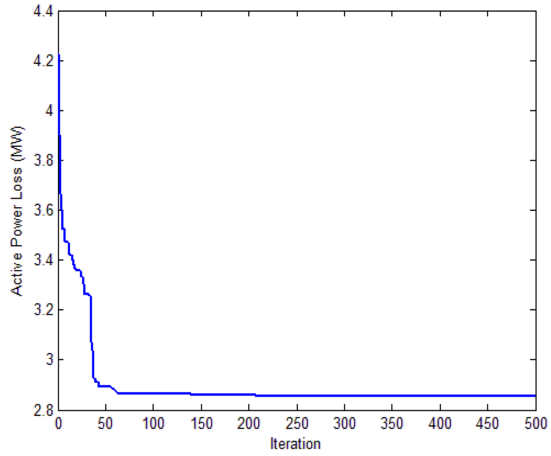

Figure 2. Convergence characteristic for solving OPF while power loss minimization (Case 2)

Table 3. Comparison of results for solving OPF with emission cost minimization (Case 3)

Method	Total emissions (ton/h)
ES	0.20477
ABC [21]	0.204826
MSFLA [17]	0.2056
SFLA [17]	0.2063
GA [17]	0.21170
PSO [17]	0.2096

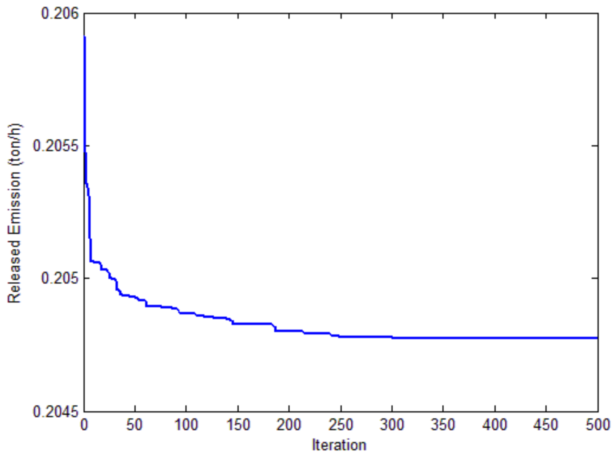

Figure 3. Convergence characteristic of solving OPF with emission cost minimization (Case 3)

B. Multi-Objective Problem Results

As mentioned, this paper uses non-dominated sorting method and crowding distance calculations in order to improve ES algorithm for solving multi objective optimal power flow problem. This section presents simulation results of evaluating performance of MOES algorithm for solving MO-OPF problem. This evaluation is down in two cases as follows:

B.1. Case 4

This case considers two different objective functions, cost of fuel and released emission, as objectives of MO-OPF problem. Table 5 demonstrates the set of control variables for minimum of both objective functions in the non-dominated repository solutions and best one chosen by fuzzy membership method.

Non-dominated Pareto optimum set consists of 50 members of solutions, in this case. Figure 4 presents solutions well spread in Pareto front. This figure demonstrates that solutions of the Pareto set are distributed well in emission-fuel cost plate.

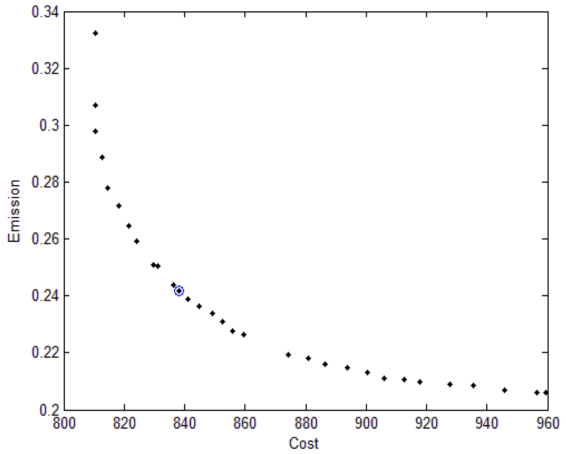

Figure 4. Set of solutions in the Pareto front (Case 4)

Table 4. Comparison of results of solving single objective OPF for introduced cases

Vars	ES			ABC [21]		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
P_{G1} (MW)	176.4677	51.256	64.121	176.791	51.5078	64.0621
P_{G2} (MW)	48.9511	80	67.349	48.5026	80	67.5849
P_{G5} (MW)	20.8388	50	50	21.5071	50	50
P_{G8} (MW)	22.0105	35	35	21.3296	35	35
P_{G11} (MW)	11.7446	30	30	12.3018	30	30
P_{G13} (MW)	12	40	40	12	40	40
V_1 (pu)	1.1	1.1	1.1	1.0811	1.0627	1.0612
V_2 (pu)	1.0881	1.097	1.099	1.0584	1.0575	1.0550
V_5 (pu)	1.0546	1.079	1.0857	1.0283	1.0385	1.0350
V_8 (pu)	1.0693	1.085	1.0966	1.0375	1.0444	1.0433
V_{11} (pu)	1.0980	1.1	1.1	1.0977	1.0739	1.0878
V_{13} (pu)	1.0990	1.1	1.0969	1.0488	1.0463	1.0535
$T_{6\text{-}9}$	0.98	1.002	0.9858	1.05	1.05	1.0125
$T_{6\text{-}10}$	0.9618	0.9133	1.0032	0.95	0.9375	1.0125
$T_{4\text{-}12}$	0.9981	0.9821	0.9911	0.9875	0.9875	1
$T_{28\text{-}27}$	0.9682	0.9690	0.9931	0.9750	0.9750	0.9875
Q_{c10} (MVA)	1.3788	0.1026	0.07	5	5	5
Q_{c12} (MVA)	4.4930	4.9243	3.07	5	5	5
Q_{c15} (MVA)	0.5845	1.41	2.7109	5	5	5
Q_{c17} (MVA)	4.3344	5	4.2525	5	5	5
Q_{c20} (MVA)	5	4.6150	3.3229	4	4	4
Q_{c21} (MVA)	1.6687	4.8433	2.8666	5	5	5
Q_{c23} (MVA)	2.7739	4.3375	2.3426	3	3	3
Q_{c24} (MVA)	5	3.3184	2.0343	5	5	5
Q_{c29} (MVA)	1.8759	2.2386	3.8361	3	2	3
Fuel cost ($/h)	799.129	967.03	943.56	800.660	967.681	944.439
Loss (MW)	8.6127	2.8565	3.0705	9.0328	3.1078	3.2470
Emission (ton/h)	0.3646	0.2072	0.2047	0.3651	0.2072	0.20482

B.2. Case 5

In this case, cost of fuel and active power loss of network are considered as objectives of MO-OPF problem. Figure 5 gives non-dominated optimal solutions which have distributed well in the Pareto front. In this case, Pareto front consist of 100 members of solution vectors. Table 6 presents control variables of minimum of both objective functions in non-dominated optimal set and proper solution among Pareto set chosen by fuzzy method. This table present MOHS algorithm results for comparison of results obtained by MOES algorithm [15].

Table 5. Results of solving multi-objective OPF in Case 4

Vars	Min. cost	Min. emis	Comp. sol	Vars	Min. cost	Min. emis	Comp. sol
P_{G1} (MW)	172.50	63.25	112.84	$T_{4\text{-}12}$	1.02	1.02	1.02
P_{G2} (MW)	46.74	67.47	58.46	$T_{28\text{-}27}$	0.98	0.98	0.99
P_{G5} (MW)	21.25	50	27.19	Q_{c10} (MVA)	0.04	0.04	0.01
P_{G8} (MW)	28.72	35	35	Q_{c12} (MVA)	0.01	0.01	0.01
P_{G11} (MW)	10.52	30	28.71	Q_{c15} (MVA)	0.04	0.04	0.42
P_{G13} (MW)	12	40	26.39	Q_{c17} (MVA)	0.04	0.04	0.04
V_1 (pu)	1.1	1.07	1.08	Q_{c20} (MVA)	0.01	0.01	0.01
V_2 (pu)	1.08	1.07	1.063	Q_{c21} (MVA)	0.03	0.03	0.03
V_5 (pu)	1.05	1.05	1.013	Q_{c23} (MVA)	0.03	0.03	0.03
V_8 (pu)	1.06	1.06	1.041	Q_{c24} (MVA)	0.04	0.04	0.04
V_{11} (pu)	1.08	1.07	1.07	Q_{c29} (MVA)	0.02	0.02	0.02
V_{13} (pu)	1.07	1.08	1.03	Fuel cost ($/h)	800.93	944.09	837.98
$T_{10\text{-}9}$	1.06	1.06	0.98	Emission (ton/h)	0.35	0.2048	0.2417
$T_{6\text{-}10}$	0.92	0.90	0.96				

VII. CONCLUSIONS

In this paper, single objective and MO-OPF were solved by ES and MOES. In this approach, fuel cost, emission and loss were considered as objective functions and Pareto optimal front was obtained by concepts of domination and crowding distance. Compromise solution was selected using fuzzy decision making method. Results of simulations demonstrated the superiority of the proposed method in comparison to the past optimization results reported in different papers and it showed usefulness of proposed method.

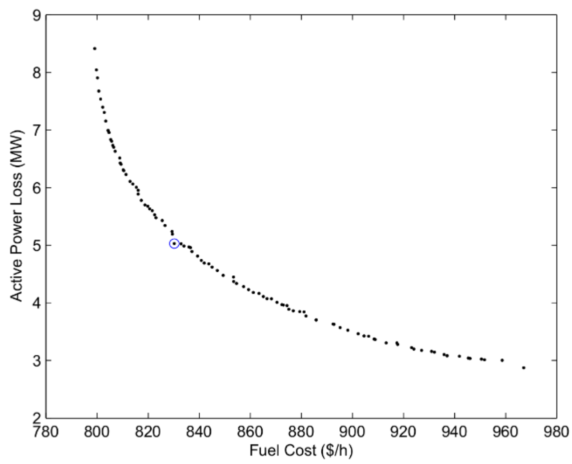

Figure 5. Set of solutions in the Pareto front Case 5

Table 6. Results of multi-objective OPF for fuel cost loss (Case 5)

Control variables	ES			MOHS [15]		
	Min. cost	Min. loss	Comp. sol	Min. cost	Min. loss	Comp. sol
P_{G1} (MW)	175.20	51.27	122.89	163.55	66.27	118.56
P_{G2} (MW)	47.98	80	48.33	51.24	79.64	51.52
P_{G5} (MW)	21.27	50	30.59	20.75	46.88	27.85
P_{G8} (MW)	24.23	35	34.95	27.95	34.88	34.98
P_{G11} (MW)	11.34	30	29.80	11.27	29.12	28.60
P_{G13} (MW)	12	40	21.94	16.67	30.05	27.10
V_1 (pu)	1.10	1.09	1.1	1.07	1.07	1.08
V_2 (pu)	1.08	1.08	1.09	1.06	1.06	1.07
V_5 (pu)	1.06	1.06	1.06	1.04	1.03	1.05
V_8 (pu)	1.06	1.07	1.07	1.04	1.04	1.05
V_{11} (pu)	1.10	1.10	1.09	1.09	1.09	1.08
V_{13} (pu)	1.10	1.10	1.09	1.09	1.09	1.08
$T_{6\text{-}9}$	1.02	1.00	1.00	1.05	0.99	0.96

$T_{6\text{-}10}$	0.91	0.91	0.90	0.91	0.91	1.00
$T_{4\text{-}12}$	0.98	0.96	0.97	0.98	0.97	0.98
$T_{28\text{-}27}$	0.96	0.96	0.96	0.94	0.94	0.97
Q_{c10} (MVA)	0.04	4.36	4.84	0.04	0.01	0.04
Q_{c12} (MVA)	0.04	4.07	3.96	0.03	0.01	0.01
Q_{c15} (MVA)	0.03	3.95	3.61	0.03	0.04	0.04
Q_{c17} (MVA)	0.03	3.56	3.17	0.04	0.02	0.04
Q_{c20} (MVA)	0.04	4.55	4.51	0.04	0.04	0.04
Q_{c21} (MVA)	0.03	3.40	3.13	0.03	0.04	0.04
Q_{c23} (MVA)	0.03	3.68	3.44	0.04	0.01	0.04
Q_{c24} (MVA)	0.05	5.00	4.92	0.04	0.02	0.01
Q_{c29} (MVA)	0.02	2.32	2.45	0.02	0.02	0.01
Fuel cost ($/h)	800.08	967.07	835.22	802.10	928.50	832.67
Loss (MW)	8.41	2.89	5.53	8.14	3.51	5.31

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