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Research paper

Multi-objective optimization considering cost, emission and loss objectives using PSO and fuzzy approach

S. Surender Reddy *

Department of Railroad and Electrical Engineering, Woosong University, Daejeon, Republic of Korea
**Corresponding author E-mail: surender@wsu.ac.kr*

Abstract

A novel approach to solve multi-objective optimization (MOO) problem which aims at minimizing fuel cost, emission release and real power loss of the system simultaneously has been proposed in this paper. Conventional minimum cost operation cannot be the only basis for generation dispatch; emission release minimization and loss minimization must also be taken care of. Power system must be operated in such a way that both active and reactive powers are optimized simultaneously. Reactive powers should be optimized to provide better volt-age profile as well as to reduce system losses. In this paper, the proposed multi-objective optimal power flow (MO-OPF) problem is solved using particle swarm optimization (PSO) and Fuzzy satisfaction maximization approach. In this paper, it is assumed that the decision maker has imprecise or fuzzy goals of satisfying all the objectives, and the proposed problem is thus formulated as a fuzzy satisfaction maximization problem which is basically a min-max problem. It is an efficient technique to obtain trade-off solution for the proposed optimization problem. The MO-OPF problem is tested on IEEE 30 bus, 6 generator system. The obtained results are found to be effective for the MO-OPF problem.

Keywords: *Emission; Evolutionary Algorithm; Fuzzy Approach; Operating Cost; Transmission Loss.*

1. Introduction

The operational aspects of power systems pose some of the most challenging problems encountered in the restructuring of electric power industry. The Clean Air Act Amendments (CAAA) of 1990 mandates that the electric utility industry reduce its sulfur oxides (SO_2) emission by 10 million tons/yr from the 1980 level. The oxides of nitrogen (NO_X) emission is required to be reduced by 2 million tons/yr from the 1980 level. In recent years, the economic dispatch problem area has taken on a suitable twist as the public has become increasingly concerned with environmental matters. The absolute minimum cost is not any more the only criterion to be met in the electric power generation and dispatching problems. The generation of electricity from the fossil fuel releases several contaminants, such as SO_2 and NO_X into the atmosphere. These gaseous pollutants cause harmful effects on human beings as well as on plants and animals [1]. In addition, the increasing public awareness of the environmental protection and the passage of the CAAA of 1990 have forced the utilities to modify their design or operational strategies to reduce pollution and atmospheric emissions of the thermal power plants.

Several alternatives have been discussed and proposed in the literature to reduce the atmospheric emissions [1]-[3]. These include installation of pollutant cleaning equipment such as electrostatic precipitators, switching to low emission fuels (i.e., low Sulphur fuels), replacement of the aged fuel-burners with cleaner ones, and dispatch the power generation to minimize emissions instead of or as a supplement to the usual cost objective of economic dispatch. The first three options require the installation of new equipment and/or modification of the existing ones that involve considerable capital outlay and, hence, they can be considered as long-term options. The emission dispatching option is an attractive short-term alternative in which both emission and fuel cost is to be minimized. In recent years, this option has received much attention because it is easily implemented and needs only small modification to the basic economic dispatching programs to include emissions. The harmful ecological effects caused by the emission of particulate and gaseous pollutants like sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) can be reduced by adequate distribution of load between the plants of a power system. However, this leads to a noticeable increase in the operating cost of the plants. The limiting levels of emissions over a schedule horizon represent additional operational constraints that are to be satisfied when finding the optimal solution for the economic dispatch (ED) problem. The characteristics of emissions of different pollutants are different and are usually highly non-linear. This increases the complexity and non-monotony city of the emission constrained economic dispatch problem.

In Reference [4], an economic, emission dispatch, loss minimization and voltage stability objectives are presented to meet an efficient operation and control. The economic and emission dispatch (EED) problem has been addressed in [5] using the hybridization of Artificial Bee Colony and Particle Swarm Optimization (PSO) algorithms. A new multi-objective optimization (MOO) approach based on non-dominated sorting to solve complex problem subject to the heavy equality and inequality constraints in power system is proposed in [6]. A novel efficient MOO technique for solving the OPF problem has been proposed in [7]. A multi-objective PSO approach for multi-objective ED problem in power system is presented in [8]. A new low level with teamwork heterogeneous hybrid PSO and artificial physics optimization algorithm is proposed in [9] to solve the multi-objective security constrained OPF problem. Reference [10] proposes a multi-objective OPF technique using PSO considering two conflicting objectives, i.e., generation cost, and environmental pollution are minimized simultaneously.

The use of multi-objective PSO algorithm to solve the ED problem in power systems while considering environmental pollution is proposed in [11]. Hybridization of conventional cuckoo search algorithm and arithmetic crossover operations are used in [12] to solve the single and MOO problems with fuel cost, emission, and total power losses as objectives. A new PSO technique for the solution of ED as well as environmental emission of the thermal power plant with power balance and generation limit constraints is proposed in [13]. A novel parameter automation strategy for PSO algorithm for solving the non-convex emission constrained ED problems is proposed in [14]. Reference [15] uses a multi-objective PSO algorithm to solve the ED problem in power systems while considering environmental pollution. Reference [16] solves the MO-OPF problem using a new hybrid technique by combining the PSO and ant colony optimization algorithms. A fuzzy mechanism based continuous genetic algorithm is employed in [17] to optimize the non-convex multi-objective problem for allocating power generation cost to all the generating units of electrical system considering system constraints.

The objective of this paper is to optimize simultaneously the system operating cost, emission release and transmission losses using the MOO algorithm, while satisfying all unit and system equality and inequality constraints. This makes the OPF problem a large-scale, highly non-linear constrained optimization problem. When the two or more conflicting objectives have to be optimized simultaneously, the multi-objective evolutionary algorithms can provide the entire set of trade-off solutions, in a single run. The operator can select a final compromised solution based on some higher level information. This provides the motivation to develop PSO based fuzzy satisfaction maximization approach to simultaneously optimize fuel cost, emission release and transmission losses. In this paper, the PSO is used for MOO of conflicting objectives. In this paper, the fuzzy satisfaction maximization approach [18] is used to determine the best compromise solution.

The rest of this paper is organized as follows: Section 2 presents the proposed problem formulation. The description of proposed MO-OPF problem using PSO and fuzzy satisfaction maximization approach is described in Section 3. Results and discussion are presented in Section 4. The contributions with concluding remarks are presented in Section 5.

2. Problem formulation

The economic dispatch (ED) and emission dispatch are considerably different. The ED deals with only minimizing the total fuel cost (operating cost) of the system violating the emission constraint. On the other hand, emission dispatch deals with only minimizing the total emission of NO_X from the system, violating the economic constraints. Therefore, it is necessary to find out an operating point, that strikes a balance between the operating cost and emission. This can be achieved by combined economic and emission dispatch problem. The objective of multi-objective PSO for cost, emission and loss minimization problem is to determine the optimal allocation of generation to minimize the total generation cost of a power system while satisfying various equality and inequality constraints.

2.1. Objective 1: minimization of fuel cost

The generator cost curves are represented by quadratic functions. The total fuel cost ($F(P_G)$) can be expressed as [19],

$$F(P_G) = \sum_{i=1}^{N} a_i P_{Gi}^2 + b_i P_{Gi} + c_i \quad (1)$$

Where N is the number of generators. a_i, b_i and c_i are the cost coefficients of the ith generator, and P_{Gi} is the active power output of the ith generator. P_G is the vector of active power outputs of generators and it is defined as,

$$P_G = [P_{G1}, P_{G2}, \ldots\ldots P_{GN}]^T \quad (2)$$

2.2. Objective 2: minimization of emission release

The emission function can be presented as the sum of all types of emission considered, such as NO_x, SO_2 thermal emission, etc., with suitable pricing or weighting on each pollutant emitted. In this paper, only NO_x emission is taken into account without the loss of generality. The amount of NO_x emission is given as a function of generator output, i.e., the sum of a quadratic and exponential function, and it is expressed as,

$$E(P_G) = \sum_{i=1}^{N} \left[10^{-2}\left(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2\right) + \xi_i \exp(\lambda_i P_{Gi})\right] \quad (3)$$

Where α_i, β_i, γ_i, ξ_i and λ_i are coefficients of the ith generator emission characteristics.

2.3. Objective 3: minimization of transmission losses

For reactive power optimization, system transmission loss minimization is considered as the objective function. Transmission power loss in each branch is calculated from the load flow solution. The converged load flow solution gives the bus voltage magnitudes and phase angles. Using these, the active power flow through the transmission lines can be evaluated. The net system power loss is the sum of power loss in each line [20].

$$TL = \frac{1}{2} \sum_{i,j} \left[G_{ij}\left(V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)\right)\right] \quad (4)$$

2.4. Constraints

2.4.1. Equality constraints

These constraints reflect the physics of the power system and they are the typical load flow equations. These constraints are formulated as,

$$P_{Gi} - P_{Di} - \sum_{k=1}^{n} V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) = 0 \quad (5)$$

$$Q_{Gi} - Q_{Di} - \sum_{k=1}^{n} V_i V_k \left(G_{ik} \sin\theta_{ij} - B_{ik} \cos\theta_{ik}\right) = 0 \quad (6)$$

In the above equations (5) and (6), i =1, 2, 3… n, and $\theta_{ik} = \theta_i - \theta_k$.

2.4.2. Inequality constraints

These constraints represent system operating limits.

a) Generating unit constraints: Generator active, reactive power outputs and voltage magnitudes are limited by their minimum and maximum constraints, and they are represented as,

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \; i = 1,2,3,\ldots\ldots, NG \quad (7)$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \; i = 1,2,3,\ldots\ldots, NG \quad (8)$$

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \; i = 1,2,3,\ldots\ldots, NG \quad (9)$$

b) Transformer constraints: Transformer taps have minimum and maximum setting limits, and they are expressed as,

$$T_i^{min} \le T_i \le T_i^{max} \; i = 1,2,\ldots, NT \quad (10)$$

c) Switchable VAR sources: The switchable VAR sources have restrictions as follows,

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max} \; i = 1,2,3,\ldots\ldots, NC \quad (11)$$

d) Security constraints: These constraints include the limits on load bus voltage magnitudes and thermal power flow limits of transmission lines, and they are represented as,

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max} \; i = 1,2,\ldots, NL \quad (12)$$

$$S_{Li} \le S_{Li}^{max}\; i = 1,2,\dots,N_l \tag{13}$$

3. MO-OPF using PSO and fuzzy satisfaction maximization approach

Though the multi-objective optimization (MOO) offers a set of solutions which are all optimal, the user needs only one final optimal solution. The user needs some higher level information to choose one solution from the set of optimal [21] solutions. Higher level information is usually taken from domain expertise. The principle of an ideal MOO procedure is to find multiple trade-off optimal solutions with a wide range of values for objectives, and then to choose one of the solutions using the higher level information [22].

In this paper, the Particle swarm optimization (PSO) algorithm is used for solving the MOO of conflicting objectives presented in Section 2.2. The reader may refer References [23]-[24] for solving the single objective OPF problem using PSO. Fuzzy satisfaction maximization approach [25] is used to determine the best compromise solution. To minimize [$f_1(x)$, $f_2(x)$] objectives simultaneously, while satisfying the set of equality and inequality constraints. Let the optimal control vector with f_1 as objective function be x_1^* and with f_2 as objective function be x_2^*. Here, the objective is to find an optimal control vector x^*, such that $f_1(x_1^*)<f_1(x^*)<f_1(x_2^*)$ and $f_2(x_2^*)<f_2(x^*)<f_2(x_1^*)$.

Due to the imprecise nature of decision maker's judgment, the objective functions are treated as fuzzy membership functions with linearly decreasing membership function. The degree of membership is assigned as 0 if ($f_i \ge f_i^{max}$). The degree of membership is assigned as 1 if ($f_i \le f_i^{min}$), and if ($f_i^{min}<f_i<f_i^{max}$), a linearly decreasing membership is assigned, and it is expressed as [22], [26],

$$\mu_i = \begin{cases} 1 & f_i \le f_i^{min} \\ \frac{f_i^{max}-f_i}{f_i^{max}-f_i^{min}} & f_i^{min} < f_i < f_i^{max} \\ 0 & f_i \ge f_i^{max} \end{cases} \tag{14}$$

For the two objective optimization problem, the following data will be available at the operating point x_1^* and x_2^*.

- At x_1^*, $f_1(x_1^*)$ and $f_2(x_1^*)$, with $f_1(x_1^*)$ at optimized value and corresponding $f_2(x_1^*)$.
- At x_2^*, $f_1(x_2^*)$ and $f_2(x_2^*)$, with $f_2(x_2^*)$ at optimized value and corresponding $f_1(x_2^*)$.

Then, $f_1^{min}=f_1(x_1^*)$ and $f_1^{max} = f_1(x_2^*)$. Similarly, $f_2^{min} = f_2(x_2^*)$ and $f_2^{max} = f_2(x_1^*)$.

If the problem is to optimize three objectives simultaneously, then x_1^*, x_2^* and x_3^* represent optimal values corresponding to three objectives considered. Correspondingly, $f_1(x_1^*)$, $f_2(x_1^*)$, $f_3(x_1^*)$, $f_1(x_2^*)$, $f_2(x_2^*)$, $f_3(x_2^*)$, $f_1(x_3^*)$, $f_2(x_3^*)$ and $f_3(x_3^*)$ are to be evaluated. Then,

$$f_1^{min} = f_1(x_1^*),\; f_1^{max}=\max[f_1(x_2^*),f_1(x_3^*)] \tag{15}$$

$$f_2^{min} = f_2(x_2^*),\; f_2^{max}=\max[f_2(x_1^*),f_2(x_3^*)] \tag{16}$$

$$f_3^{min} = f_3(x_3^*),\; f_3^{max}=\max[f_3(x_1^*),f_3(x_2^*)] \tag{17}$$

Therefore, in case of two objective optimization problem [21], [27],

$$\mu_1 = \begin{cases} 1 & f_1 \le f_1(x_1^*) \\ \frac{f_1(x_2^*)-f_1}{f_1(x_2^*)-f_1(x_1^*)} & f_1(x_1^*) < f_1 < f_1(x_2^*) \\ 0 & f_1 \ge f_1(x_2^*) \end{cases} \tag{18}$$

$$\mu_2 = \begin{cases} 1 & f_2 \le f_2(x_2^*) \\ \frac{f_2(x_1^*)-f_2}{f_2(x_1^*)-f_2(x_2^*)} & f_2(x_2^*) < f_2 < f_2(x_1^*) \\ 0 & f_2 \ge f_2(x_1^*) \end{cases} \tag{19}$$

The above equations (18) and (19) give the membership values of two objective functions. The final objective is to maximize the fuzzy satisfaction parameter (λ). The λ is obtained as the intersection of the two degrees of membership, i.e., minimum of (μ_1, μ_2). This would be minimum of (μ_1, μ_2, μ_3) for the case of three objective optimization. The solution with maximum overall satisfaction is the best compromise solution. Effectively, this approach uses the PSO algorithm for deciding the two extremes of the objective functions (i.e., single objective optimization problem) that are to be optimized simultaneously. Then, the PSO is used for generating the optimal trade-off between the two extremes of the objective function values and for maximization of overall fuzzy satisfaction parameter (λ) [21].

3.1. Algorithm for solving the MO-OPF problem

The step-by-step algorithm for solving the MO-OPF problem using the PSO and fuzzy satisfaction maximization approach is presented next:

Step 1: Read the system data.

a) Data required for PSO.

(Swarm size, particle size, number of generators, generator voltage magnitudes, transformers with taps and shunts, number of discrete control steps for shunts and taps, cost coefficients, maximum and minimum power output of generators, voltage limits of buses, maximum and minimum values of taps, and shunts, line flow limits, c_1=2.05, c_2=2.05, itermax).

b) Data required for load flow solution.

(n, Nl, nslack, max iterations, epsilon, line data, bus data, shunts, line flow limits).

Step 2: Form Y_{bus}.

Step 3: Form constant slope matrices and decompose using cholesky decomposition.

Step 4: Set discrete tap control vector ttap.

Ttap (1) = t_{min}; (min tap value)

Ttap (i) = ttap (i-1) + 0.0125; for i=1: number of discrete control steps for taps.

Step 5: Set discrete shunt control.

Sshunt (1) = sshunt (min tap value)

sshunt (i)= sshunt (i-1)+0.01; for i=1:number of discrete control steps for shunts.

Step 6: Randomly initialize the swarm of particles.
Step 7: Randomly initialize velocities of all particles.
Step 8: Initialize G_{best} and P_{best} particles to zero.
Step 9: Set iteration count =1.
Step 10: Set particle count (k =1).
Step 11: Use control variables from particle and modify Y_{bus} elements due to taps and shunts.
Step 12: Run load flow analysis. From converged load flow solution compute slack bus power, fuel cost, line losses, and voltage stability evaluation index.
Step 13: Check for limits on load bus voltage magnitudes, generator reactive power limits, slack bus power limit, and line flow limit.
Step 14: Calculate penalty factor for violated functional constraints.
Step 15: Compute the augmented objective function.
Step 16: Calculate fitness of particle considering the selected objective function f_1.
Step 17: Compute P_{best} particle.

Step 18: Check if $G_{best}<P_{best}(k)$
if yes, set $G_{best}=P_{best}(k)$.
Step 19: Based on P_{best} particle and G_{best} particle compute velocities of particles. Calculate new positions for particles and enforce the limits on all the control variables.
Step 20: Check if (k<number of particles)
if yes, increment particle count, k = k+1, and go to Step 11.
Step 21: Check if (iteration<itermax)
if yes, increment iteration count by 1 and go to Step 10.
Step 22: Repeat Steps 6 to 21 for selected second objective function f_2.
Step 23: Identify the boundaries of the optimal front considering both the optimal objective function values, and repeat Steps 6 to 12.
Step 24: Evaluate fuzzy satisfaction parameter (λ) as minimum of fuzzy membership values of f_1 and f_2.
Step 25: Assign fitness to each particle as λ.
Step 26: Repeat steps 17 to 20.
Check if (iteration<itermax)
If yes, increment iteration count by 1 and go to Step 10
Step 27: Print out the best compromise solution as the one with maximum satisfaction parameter (λ).

4. Results and discussion

In this paper, the simulation results are provided to highlight the main features of proposed PSO and fuzzy satisfaction maximization approach. The standard IEEE 30 bus, 6 generator test system is considered to show the effectiveness of the proposed approach [28]. As mentioned earlier, three objective functions, i.e., fuel cost, emission release and system transmission losses are considered. The PSO parameters used in this paper are: Swarm size: 60, size of particles: 24, maximum number of generations: 200, acceleration constants (c_1 and c_2): 2.05, inertia weight: 1.2 and constriction factor: 0.7295. The generator capacity limits and the fuel cost coefficients data of IEEE 30 bus test system are presented in Table 1 [28-29]. The emission coefficients of generators are presented in Table 2. The static shunt capacitors data is presented in Table 3.

Table 1: Generator Capacity Limits and Fuel Cost Coefficients Data

Bus No.	Fuel Cost Coefficients			P_{Gi}^{max} (MW)	P_{Gi}^{min} (MW)	Q_{Gi}^{min} (MVAR)	Q_{Gi}^{max} (MVAR)
	a	b	c				
1	0.00375	2.00	0	200	50	-20	200
2	0.01750	1.75	0	80	20	-20	100
5	0.06250	1.00	0	50	15	-15	80
8	0.00830	3.25	0	35	10	-15	60
11	0.02500	3.00	0	30	10	-10	50
13	0.02500	3.00	0	40	12	-15	60

Table 2: Generator Emission Release Functions Values

Generator No.	Emission release function coefficients				
	α	β	γ	ξ	Λ
1	4.091	-5.543	6.490	2.0e-4	2.857
2	2.543	6.047	5.638	5.0e-4	3.333
3	4.258	-5.094	4.586	1.0e-6	8.000
4	5.326	-3.550	3.380	2.0e-3	2.000
5	4.258	-5.094	4.586	1.0e-6	8.000
6	6.131	-5.555	5.151	1.0e-5	6.667

Table 3: Static Shunt Capacitor Data

Bus No.	Susceptance (in p. u.)
10	0.190
24	0.043

Initially, the minimum and maximum values of each original objective function are computed in order to obtain the last compromise solution. Minimum values of the objectives are obtained by giving full consideration to one of the objectives and neglecting the others. In this paper, three objective functions are considered. Therefore, fuel cost, emission release and system losses are optimized individually to obtain minimum values of the objectives. Owing to the conflicting nature of the objectives, emission and system loss have maximum values when fuel cost is minimum. The minimum and maximum values of three objectives are presented in Table 4.

Table 4: Minimum and Maximum Values of 3 Objective Functions

Objective Functions	Maximum Value	Minimum Value
Fuel cost ($/hr)	860.65	800.62
Emission (ton/hr)	0.342	0.389
System losses (MW)	3.543	10.083

In this paper, 3 case studies are simulated and they are solved using the PSO and fuzzy satisfaction maximization approach.

- Case Study 1: Optimizing Fuel cost and Emission release objectives simultaneously.
- Case Study 2: Optimizing Fuel Cost and transmission losses objectives simultaneously.
- Case Study 3: Optimizing Fuel cost, emission release and transmission losses objectives simultaneously.

4.1. Case study 1

As mentioned earlier, in this Case, two objective functions, i.e., fuel cost and emission release are optimized simultaneously using the PSO and fuzzy satisfaction maximization approach. The distribution of the non-dominated solutions in the Pareto-optimal front using the proposed PSO and fuzzy satisfaction maximization approach is shown in Figure 1. From this figure, it is clear that the solutions are diverse and well distributed over the trade-off curve. The best compromised solution can be obtained using the fuzzy min-max approach. The best compromised solution obtained in this case has the total fuel cost of 824.6$/hr and the emission release of 0.3569tons/hr.

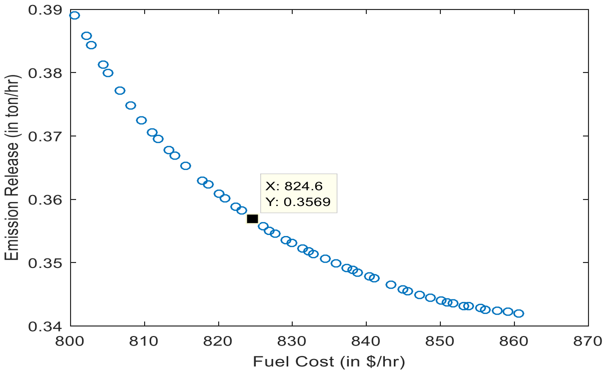

Fig. 1: Pareto-Optimal Front for Case Study 1.

4.2. Case study 2

In this Case, two objective functions, i.e., fuel cost and transmission loss minimizations are optimized simultaneously using the PSO and fuzzy satisfaction maximization approach. The distribution of non-dominated solutions in the Pareto-optimal front using the proposed PSO and fuzzy satisfaction maximization approach is shown in Figure 2. From this figure, it is clear that the solutions are diverse and well distributed over the trade-off curve. The best compromised solution can be obtained by using the fuzzy min-max approach. The best compromised solution obtained in this case has total fuel cost of 822.4$/hr and total transmission losses of 6.034MW.

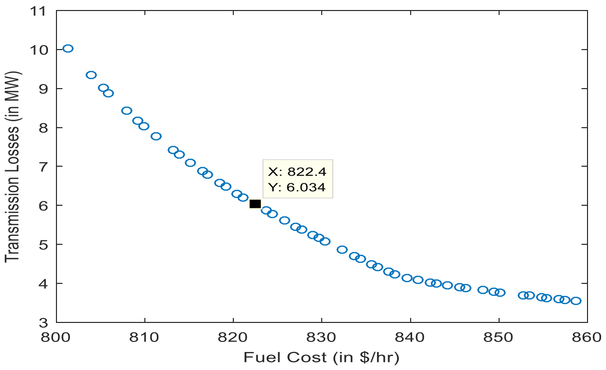

Fig. 2: Pareto-Optimal Front for Case Study 2.

4.3. Case study 3

In this Case, all the three objective functions, i.e., fuel cost, emission release and transmission loss minimizations are optimized simultaneously using the PSO and fuzzy satisfaction maximization approach. The distribution of the non-dominated solutions in the Pareto-optimal front using the proposed PSO and fuzzy satisfaction maximization approach is shown in Figure 3. From this figure, it is clear that the solutions are diverse and well distributed over the trade-off curve. The best compromised solution can be obtained using the fuzzy min-max approach. The best compromised solution obtained in this case has the total fuel cost of 829.9$/hr, emission release of 0.3531tons/hr and the total transmission losses of 5.086MW.

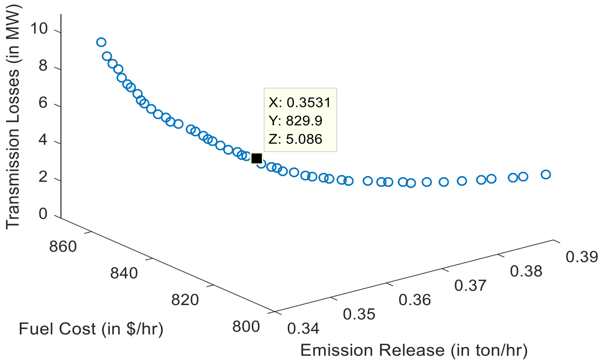

Fig. 3: Pareto-Optimal Front for Case Study 3.

From the above simulation results, it can be observed that the proposed approach is efficient for solving MOO problems where multiple Pareto-optimal solutions can be found in single simulation run. The non-dominated solutions in the obtained Pareto-optimal set are well distributed and have satisfactory diversity characteristics.

5. Conclusion

In this paper, a multi-objective optimal power flow (MO-OPF) problem is solved using the particle swarm optimization (PSO) based fuzzy satisfaction maximization approach with three competing objectives, i.e., fuel cost, emission release and system transmission loss objectives. If the problem is defined for simultaneous optimization of several conflicting objectives, then the meta-heuristic algorithms can be used to capture the multiple optimal solutions in its final population. The effectiveness of the proposed approach is implemented on standard IEEE 30 bus system. The simulation results showed that the proposed approach is efficient for solving multi-objective optimization problems where multiple Pareto-optimal solutions can be found in one simulation run. In addition, the non-dominated solutions in the obtained Pareto-optimal set are well distributed and have satisfactory diversity characteristics.

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