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Optimal Flow of Active Power with Pollution Control Using Multi-objective Particle Swarm Optimization Techniques

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Abstract- This paper gives the solution of optimal power flow (OPF) problem of medium-sized power systems via an artificial intelligence algorithm. The objective is to minimize the total fuel cost of generation and environmental pollution caused by fossil based power generating units.System performance is also maintained by limiting generator real and reactive power outputs and power flow of transmission lines in acceptable limits. The power flow equations and load balance equation are considered as equality constraints. The performance analysis of this OPF problem using the Particle Swarm Optimization technique is carried out by checking various combinations of values of the associated parameters.The bi-objective problem of generation cost and emission dispatch is solved via weighted sum method for different combinations of weights and a multi-objective problem of minimizing power generation cost and flue gases (NO_x, CO_2, SO_2), is solved by a new algorithm named as Multi-Objective PSO (MOPSO) technique, to find out optimal solution and optimal value of weights.Simulation results for the IEEE 30-bus network with 6 generators system show that by proposed method, an optimum solution can be given quickly.

Keywords: *Optimal power dispatch,Swarm Intelligence, Particle swarm optimization (PSO), Multi-Objective Particle swarm optimization(MOPSO), Pareto- Front technique.*

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I. INTRODUCTION

Optimal active power dispatch problem is also known as economic load dispatch problem which can be defined as “the process of allocating generation levels to the generating units, so that the entire system load is supplied most economically”. In economic dispatch strategy, the operating cost is reduced by proper allocation of the amount of power to be generated by units.With the development of our society power demand and per capita energy consumption has also increased. To deliver this demand power generation is increasing which also results in increased pollution. Now a days Indian government and power associations concentrating on the reduction of the amount of pollutants from fossil fuel power generating units. At present power engineers are facing problem of generating power in an effective manner to cope-up with load demand and minimize environmental hazards. Optimization is a good tool to handle such problems which is effectively used in areas of optimal power flow (OPF) such as Power system operation, planning, analysis and energy management. In power system operations and planning, OPF is the best option because it provides facility of handling the multi-objective functions. It also makes calculations and decision making fast and easier. So, here optimal power flow (OPF) is concerned with the minimization of economic generation and minimization of environmental harmful effects like gases extortion from power generating plant.

Today various computer based algorithms are available in mathematics to find the optimum solution of any linear or non-linear function. These algorithms are broadly classified as conventional and evolutionary techniques. Some of conventional methods like Gradient method (GM), Interior point method (IP), Linear programming (LP) have been proposed for the optimal power flow problem successfully[1,9]. But objective function of OPF problem is not a linear one and it is non- differential too[15].So, the problem with conventional methods while solving the OPF problem is the solution may be local optimum, not a global optimum[9]. The **second problem** with conventional methods is, if the state variables are defined in very short range than solution may become infeasible[3].**Third problem** with conventional methods is calculations of Lagrange Multipliers and step length is required[1].To overcome these problems, Evolutionary Algorithms (EA)are introduced e.g. GA, PSO, ACO and Stochastic Algorithms (SA) etc. These all algorithms are nature inspired. These further classified as heuristic and meta-heuristic algorithms.

Alan Turing was the first who used heuristic algorithms in 1948. After that in the two decades,1960s and 1970s Evolutionary Algorithms were developed. Today these algorithms are very popular to solve the real-world optimization problems. These are equally useful in Optimal Power flow problems[3-5]. Genetic Algorithm (GA),Particle swarm optimization (PSO), Differential Evolution (DE)[3-6, 9-10,13] have been proposed for minimization of cost of active power as an objective function. Particle swarm optimization have been used in some multi-objective problems[2,7] considering various cost functions like combined cost of active and reactive power[13].In the optimal dispatch of active power, generators are rescheduled to minimize the cost but minimization of emission effect increases system operating cost. In order to minimize emission with economic dispatch a combined composite function of cost and emission is considered.

In this paper, performance of PSO and MOPSO is tested in solving the multi-objective problem of optimal active power dispatch. The proposed approach have been examined and tested on the standard IEEE 30-bus system with 6 generators. The objective of this paper is to solve the multi-objective problem of economic power dispatch; having four objectives these are fuel cost and environment impact due to SO2, CO2 and NO_xgaseous pollutants.

II. PROBLEM FORMULATION

The objective of optimal power flow is to identify the control variables which minimize the objective function of cost and pollution. This is formulated mathematically as follows:

A. Bi-Objective Problem of Optimal Active Power Dispatch

1) Minimization of fuel cost with real power output

The fuel cost of each fossil fuel fired generator can be expressed as a single quadratic function. Total fuel costin terms of real power output and cost coefficients (a, b, c) can be expressed as [13]:

$$f(Pg) = \sum_{i=1}^{NG} a_i Pg_i^2 + b_i Pg_i + c_i (\$/h) \qquad (1)$$

2) Minimization of emission dispatch

The emission function can be expressed asthe sum of all types of emissions as flue gases, particulate materials and thermal radiation with suitable pricing for each pollutant emitted. The emission dispatch problem can be formulated as an optimization function in terms power output and emission coefficients (d, e, f) of each unit [2].

$$E(Pg) = \sum_{i=1}^{NG} d_i Pg_i^2 + e_i Pg_i + f_i (Kg/h) \qquad (2)$$

By introducing a price penalty factor Pf (H) the above mentioned optimization problems can be converted into a single bi-objective function. Here the function of H in terms of max Pg of each unit is given as [2]

$$H = \frac{\sum_{i=1}^{NG} a_i P\max_i^2 + b_i P\max_i + c_i}{\sum_{i=1}^{NG} d_i P\max_i^2 + e_i P\max_i + f_i} (\$/Kg) \qquad (3)$$

Here, H is price penalty factor, which combines the emission cost with the normal fuel costs. Thus the total cost function (CF) of the system is the addition of fuel cost and the implied cost of emission[2].

$$CF = f(Pg) + H * E(Pg) \qquad (4)$$

The above bi-objective function solved by weighted sum method by introducing weighting factorsw_{eco} and w_{emi}, and combined cost function can be expressed as follows[6]:

$$CF = weco * f(Pg) + wemi * \{H * E(Pg)\} \qquad (5)$$

The two weighting factors w_{eco} and w_{emi} respectively for fuel cost and emission cost function may vary in the range of 0.0 to 1.0.In case of $w_{eco}$is 1.0 and $w_{emi}$is 0.0 it yield the classical economic dispatch problem while the pure emission dispatch is the case of $w_{eco} = 0.0$ and $w_{emi} = 1.0$.To establish the combined economic and emission dispatch problem, both weighting factors should be greater than 0.0 and less than 1.0.

B. Multi-Objective Problem of Optimal Active Power Dispatch

The generation of electricity from fossil fuel releases several contaminants, such as sulphur dioxide (SO2), nitro-gen oxides (NOx), and carbon dioxide (CO2) into the atmosphere. Atmospheric pollution affects not only humans but also other life forms such as animals, birds, fish and plants. It also causes damage to materials, reducing visibility as well as causing global warming. Minimization of all these chemicals with the cost minimization forms a multi-objective problem.

1) Minimization of power generation cost

The generation cost of each fossil fuel fired generator can be expressed as a single quadratic function in terms of real power output and cost coefficients (a, b, c) as [18]:

$$F(1) = \sum_{i=1}^{NG} a_i Pg_i^2 + b_i Pg_i + c_i (\$/h) \qquad (6)$$

2) Minimization of emission ofSO_2 gas

The emission of SO_2 gas of fossil fuel fired generator can be expressed as a single quadratic [18]:

$$F(2) = \sum_{i=1}^{NG} l_i Pg_i^2 + m_i Pg_i + n_i (kg/h) \qquad (7)$$

3) Minimization of emission ofCO_2 gas

The emission of CO_2 gas of fossil fuel fired generator can be expressed as a single quadratic [18]:

$$F(3) = \sum_{i=1}^{NG} x_i Pg_i^2 + y_i Pg_i + z_i (kg/h) \qquad (8)$$

4) Minimization of emission ofNOx gas

The emission of NOx gas of fossil fuel fired generator can be expressed as a single quadratic [18]:

$$F(4) = \sum_{i=1}^{NG} d_i Pg_i^2 + e_i Pg_i + f_i (kg/h) \qquad (9)$$

A. System Constraints

In this paper following equality and inequality constraints are considered.

1) Equality Constraints

$$\sum_{i=1}^{NG} Pg_i - \sum_{i=1}^{NB} Pd_i - Ploss = 0 \quad (10)$$

Above equation isknown as "Power balance equation". Where Ng is no. of generating units and NB is the number of load buses, Pg is the active powergenerated;Pd is the activepower load, respectively.

2) Inequality Constraints

Generator power limits: generated power output of all the 6 generators is varied in their upper and lower range:

$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max} \quad (7)$$

Here NG shows the number of generators, (i= 1, 2 ......NG)

III. MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION

1) Overview

PSO is one of theevolutionary algorithms(EA), which is inspired by the social flocking behaviour of birds and the schooling behaviour of fish. As like other EAs, PSO is also initialized with some random solutions. All the particles in the PSO fly through-out the problem space. To have all the particles being located in the optimal position in a multi-dimensional space, is the ultimate goal of PSO technique.

Thus the behaviour of the flock or swarm is based on a combination of threeimportant features:

1. **Cohesion**—Stick together.
2. **Separation**—doesn't come too close.
3. **Alignment**—Follow the general heading of the flock.

2) *Initialization*

Inthe PSO algorithm, each individual "i", called particle, represents a solution to the optimization problem and set of these individual solution forms a vector of decision variables, Xi. The initial particles are generated randomly in between their limits by uniform distribution using following equation [23].

$$X_i = X_i^{\min} + rand() * (X_i^{\max} - X_i^{\min}) \quad (8)$$

Here, NP shows the number of particles,(i=1, 2.....NP)

3) Velocity of Particles

In PSO algorithm particles follow the fittest member of the swarm and move toward historically good areas of the provided space. In order to achieve this,individuals are associated with some velocity, v.Starting from zero value in each iteration velocity is updated by the global best position in the problem space called as **Gbest** and the best known individual position of a particle called as **Pbest**using following equation[1].

$$v_{ij}^{t+1} = wv_{ij}^{t} + c_1R_1(Pbest^t - X^t) + c_2R_2(Gbest^t - X^t) \quad (9)$$

Wherev_{ij} is velocity of jth member of ith particle which is bounded in its min-max limits and w is inertia-weight[18]:

$$w = w^{\max} - \frac{(w^{\max} - w^{\min}) * iteration}{\max iteration} \quad (10)$$

Here, R_1& R_2 are the random numbers generated between 0 and 1. C_1& C_2can varyin range of 0-4 but these are adjusted such as $C_1 + C_2=4$. In this paper $C_1=C_2= 2$ [13].

4) Update the solution vector

At each iteration (generation), the position vector of swarms is updated by adding the velocity 'v' [18].

$$X^{t+1} = X^t + v^{t+1} \quad (11)$$

5) Constriction Factor

With the aim of eliminating velocity clamp and encouraging convergence, Clerc and Kennedy[2] proposed a constriction factor.Constriction factor can lie in interval of 0.5 to 1.0[23]. This constriction factor, "k" is involved in theequation of velocity update as follows:

$$v_{ij}^{t+1} = k * \{wv_{ij}^{t} + c_1R_1(Pbest^t - X^t) + c_2R_2(Gbest^t - X^t)\} \quad (12)$$

6) Multi-Objective PSO

The difficulty of finding an optimal solution for a multi-objective problem lies in the possible conflicts that may exist between the optimal solutions for the separate objectives. The best solution for a certain objective might be the worst for another. Solving these conflicts is the essence of finding an "optimal" solution on multi-objective ground. There are two approaches for solving multi-objective problems. **First** isby converting the multi-objective probleminto a single objective problem. This often carried out by gathering all objectives in a weighted function.But there is a problem of adjusting weighting factor with this approach.

The **second approach** is based on Pareto optimality (PO) concept, where a set of optimal solutions is found, instead of one optimal solution. The reason for the optimality of many solutions is that no one can be considered to be better than any other with respect to all objective functions. Compared with traditional algorithms, PO is more suitable for solving multi-objective problems[14].The proposed approach,Multi-Objective PSO is proposed to solve the problem of adjusting weighting factors by uniting "Pareto-dominance principles" with PSO[5].

a) **Efficient solution:** A feasible solution is called efficient solutionif there is no other feasible solution where all the objectives perform better[5].

ISSN: 2454-4248
17 – 23

b) **Efficient Frontier:** The set of all efficient solutions is called an efficient frontier. Clearly, under any reasonable definition of optimality, an optimal solution to a multi-objective problem must come from within the efficient frontier.

c) **Pareto Curve:**The image of the efficient set, i.e., the image of all the efficient solutions, is calledPareto front or Pareto curve/surface. The shape of the Pareto surface indicates thenature of the trade-off between the different objective functions.

The relationship between the weights of objective function and the Pareto curve is such that, a uniform spread of weight parameters does not produce a uniform spread of points on the Pareto curve. It isobserved about this fact is, all the points are grouped in certain portion of the Pareto front, while some portion of the trade-off curve have not been produced.

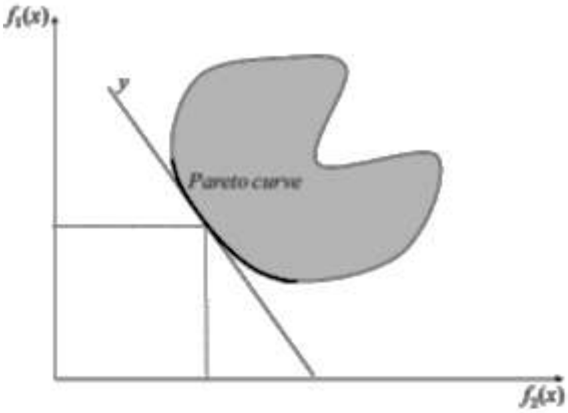

Figure 1 Geometrical representation of the weight-sum approach in the convex Pareto curve

IV. SIMULATION STUDY & RESULTS

Case-I Solution of Bi-Objective Problem of Optimal Active Power Dispatch

a) System under study

The proposed approach is implemented and tested on a test bed of IEEE- 30 bus 6-gen system.IEEE 30 bus system consists of 48 branches, 6 generators-buses and 22 load-buses. Here, **Bus-1** is considered as *slack bus*,**2,5,8,11,13**are PV-Buses and remaining others are PQ-buses. All the first load flow analysis is done with the system data[6].

TABLE-I Parameters of PSO set for OPF

S. No.	Parameter	Value
1	No. of Particles in PSO (N)	30
2	No. of Variables in PSO (D)	06
3	Penalty factor in PSO (k)	10
4	Max Iterations	100
5	Constriction Factor in MPSO	0.5

b) Optimal solution obtained

To demonstrate the effectiveness of Particle swarm optimization (PSO) on IEEE 30 bus system MATLAB programs have been developed for Bi-objective optimal active power dispatch problem. Here objective is to minimize the generation cost and emission dispatch with satisfying load and losses. As mentioned above, the real power outputs of all the generators are varied in their range.

TABLE-IIFuel cost ($/h) and Emission dispatch (Kg/h) with different weights

S. No.	Weco	Wemi	Fuel cost ($/h)	Emission dispatch (Kg/h)
1	1.0	0.0	805.93	466.43
2	0.7	0.3	811.26	417.66
3	0.5	0.5	823.93	372.83
4	0.3	0.7	848.42	355.07
5	0.0	1.0	899.23	350.10

Minimized fuel cost and emission dispatch are calculated by PSO with different sets of weights. In all the cases results obtained by PSO technique are in equal proportion. The problem occurred while solving multi-objective problem by weighted sum method is deciding optimal value of weights.

Case-II Solution ofMulti-Objective Problem of Optimal Active Power Dispatch

a) System under study

IEEE-30 bus 6-gen systemis considered for study of multi-objective optimal active power dispatch problem. The system data like fuel cost coefficients and emission coefficients of CO_2, SO_2, NO_Xgases are considered as follows[6].

TABLE-III Fuel cost Coefficients of System

Gen. Unit	a ($/MWh^2)	b ($/MWh)	c ($/h)
1	0.0020	8.43	85.63
2	0.0038	6.41	303.77
3	0.0021	7.42	847.14
4	0.0013	8.30	274.22
5	0.0021	7.42	847.14
6	0.0059	6.91	202.02

TABLE-IVCO_2 emissionCoefficients of System

Gen. Unit	x (Kg/MWh2)	y (Kg/MWh)	z ($/h)
1	0.26	-61.01	5080.14
2	0.14	-29.95	3824.77
3	0.10	-9.55	1342.85

ISSN: 2454-4248
17 – 23

4	0.10	-12.73	1819.62
5	0.10	-9.55	1342.85
6	0.40	-121.98	11381.07

TABLE-VSO_2 emission Coefficients of System

Gen. Unit	l (Kg/MWh2)	m (Kg/MWh)	n ($/h)
1	0.0012	5.05	51.37
2	0.0023	3.84	182.26
3	0.0012	4.45	508.52
4	0.0008	4.97	165.34
5	0.0012	4.45	508.52
6	0.0035	4.14	121.21

TABLE-VINOx emission Coefficients of System

Gen. Unit	d Kg/MWh2)	e (Kg/MWh)	f ($/h)
1	0.0063	-0.38	80.90
2	0.0064	-0.79	28.82
3	0.0031	-1.36	324.17
4	0.0067	-2.39	610.25
5	0.0031	-1.36	324.17
6	0.0061	-0.39	50.38

TABLE-VIIDifferent sets of weighting factors and corresponding optimized results of fuel cost and emitted gases

S. No.	W1	W2	W3	W4	Fuel Cost ($/h)	CO2 emission (Kg/h)	SO2 emission (Kg/h)	NOx emission (Kg/h)
1	0.45	0.3644	0.0633	0.1223	4906.88	17247.16	2943.39	1315.34
2	0.45	0.1271	0.3843	0.0385	4844.43	15299.58	2906.00	1278.80
3	0.45	0.1558	0.2558	0.1382	4854.52	15361.76	2912.04	1316.88
4	0.45	0.5433	0.0151	0.0324	4906.46	16959.56	2943.16	1376.44
5	0.45	0.3939	0.1409	0.0151	4821.13	15200.21	2882.10	1270.68
6	0.45	0.1596	0.1462	0.2440	4837.52	15258.53	2901.88	1289.26
7	0.45	0.1271	0.2058	0.2169	4855.00	15259.28	2912.31	1305.44
8	0.45	0.2478	0.2719	0.0302	4915.72	16809.03	2948.70	1363.44
9	0.45	0.4865	0.0642	0.3140	4857.65	16566.20	2913.95	1318.44
10	0.45	0.2803	0.1857	0.0838	4875.06	16002.32	2824.36	1336.86

TABLE-VIIIOptimal setting of weights and control variables for multi-objective function

S. No.	Weighting Factors, Wi		S. No.	Generator's Power Output, Pgi (MW)	
1	W1	0.4500	1	Pg1	106.78
2	W2	0.3939	2	Pg2	77.02
3	W3	0.1409	3	Pg5	33.52
4	W4	0.0151	4	Pg8	28.12
			5	Pg11	22.05
			6	Pg13	27.25
			7	Total Power Gen (MW)	293.54

TABLE-IXMinimized fuel cost and gases emission by MOPSO technique

S. No.	Parameter	With initial settings of generatorpower output	With optimal setting of generator power output
1	Total Cost of gen. ($/h)	4833.40	4821.10
2	Total NOx dispatch (Kg/h)	1288.95	1270.70
3	Total SO2 dispatch (Kg/h)	2899.48	2882.10
4	Total CO2 dispatch (Kg/h)	16881.55	15200.0

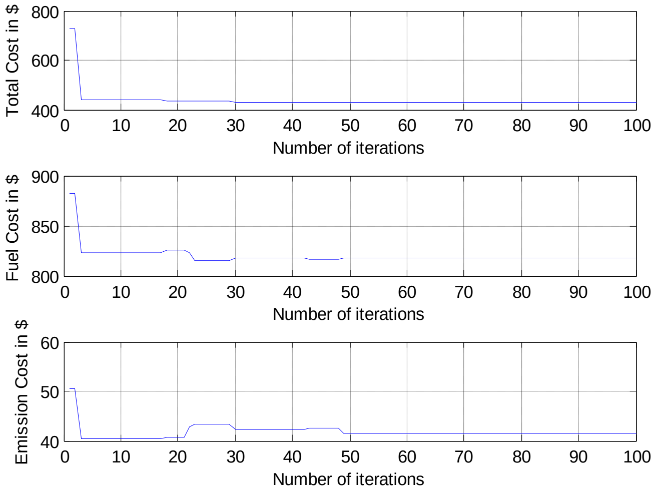

Figure 2 Characteristics curve for Bi-objective ELD problem solved by PSO for case of equal weights

V. CONCLUSION

This paper shows the solution of an optimal power flow (OPF) problem for medium-sized power systems using an artificial intelligence algorithm of real type. The bi-objective problem of generation cost and emission dispatch is solved via. weighted sum method for different combinations of weights. The objective, minimization of total fuel cost and environmental pollution caused by fossil based thermal generating units of IEEE 30 bus 6 generator systems is considered. It is minimized by **10.42%** and **3.54%** respectively using particle swarm optimization technique (PSO). The power flow equations and load balance equation are considered as equality constraints.A multi-objective problem of minimization of power generation cost and flue gases (NOx, CO2, SO2) dispatch for the same system is also solved to find-out optimal solution by proposed technique. Results of analysis claims that the proposed technique i.e. Multi-objective PSO performs better than the classical approach of weighted sum method in solving multi-objective optimal power flow problems.

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