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DEMO Based Optimal Power Purchase Planning Under Electricity Price Uncertainty

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***Abstract*—**Due to the deregulation of the Electric Supply Industry and the resulting emergence of electricity market, the volumes of power purchases are on the rise all over the world. In a bid to meet the customer's demand in a reliable and yet economic manner, utilities purchase power from the energy market over and above its own production. This paper aims at developing an optimal power purchase model with two objectives viz economy and environment ,taking various functional operating constraints such as branch flow limits, load bus voltage magnitudes limits, unit capacity constraints and security constraints into consideration.The price of purchased power being an uncertain variable is modeled using fuzzy logic. DEMO (Differential Evolution For Multi-objective Optimization) is used to obtain the pareto-optimal solution set of the multi-objective problem formulated. Fuzzy set theory has been employed to extract the best compromise non-dominated solution. The results obtained on IEEE 30 bus system are presented and compared with that of NSGAII.

***Keywords*—**Deregulation, Differential Evolution, Multi objective Optimization, Pareto Optimal Set, Optimal Power Flow

I. INTRODUCTION

THE electric power industry has been deregulated and restructured all over the world which has resulted in market-based competition by creating an open market environment. To ensure economic and reliable operation of the power system utilities go for power purchases when desirable. In state-utilities in India, the state load is supplied by the state-owned generation plants as well as by power purchased from Central Government owned generating plants and the power market. Power purchased from central sector is charged through ABT [1] and that purchased from power market is charged at Market Clearing Price (MCP). Thus, the optimum scheduling problem becomes distributing load amongst internal generators and power purchased from the central sector and power market, so as to minimize cost of generation. However, the uncertainty associated with the MCP makes this optimization a complex task. In this paper the power purchased from the central sector is not considered. The power available in market is modeled as a 'market-generator'. Thus, load demand will be served by a set of internal generators and market generator. generators share the maximum load along with power to be purchased from market depending on market price. Hence the development of an optimal generation and power purchase schedule is a much desired requirement under such a scenario. The price of electricity during a power purchase is usually an uncertain variable. Modeling the same is a complex task because of uncertainty resulting from the inherent dependence of price to other, sometimes unpredictable factors, such as variations in demand and supply situation. This type of uncertainty may not follow the nature of a probabilistic distribution and is best modeled by fuzzy logic for representing the relationship among different variables[2].In addition to this, following the passage of Clean Air Act Amendments in November 1990 there is an increased emphasis on emission reduction. This requires that utilities should also include into account emissions as objective to be minimized, thereby making the OPF problem a multi-objective one. In contrast to single-objective optimization that tries to determine one global best solution for an optimization problem, generally several trade-off solutions are generated in multi-objective optimization, dubbed as the pareto optimal set.A Pareto optimal set is a set of solutions that are non-dominated with respect to each other. Pareto optimal solution sets are often preferred to single solutions because the final solution of the decision-maker is always a trade-off.

The literature includes several OPF studies that dealt with multi-objectives and applied evolutionary optimization techniques,details of which can be found in [3]. NSGA, NPGA, SPEA, NSGA-II[4], MOPSO and fuzzified MOPSO (FMOPSO) , fuzzy clustering-based particle swarm (FCPSO) algorithms, etc., constitute the leading multi-objective evolutionary computation approaches that have been applied to solve the multi-objective Economic Emission Dispatch (EED) problem.With the power system open access, the economic/emission dispatch problem is extended to include power transaction from the market. In [2] a methodology to evaluate power purchases in an uncertain environment is presented. However, a dc load flow formulation was used and network losses and other security constraints were not considered. Moreover emission from the thermal units is not considered. In [5] an optimization-based method for the integrated consideration of power purchase transactions and the scheduling of thermal units is presented based on the augmented Lagrangian decomposition and coordination method. Again, a single-objective formulation is used as emission is not considered.Rui Ma et al formulated a multi-objective optimal transaction planning problem based on Interior point method [6]. A similar optimal power purchase planning problem is formulated and solved using cataclysmic genetic algorithm in [7]. A multi objective power purchase and distribution planning model was developed by Zhang et al in [8]. However, emission is not considered in [7] and [8].Also, the problem is not treated as a true multi objective problem in any of these works.

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In this paper the optimal power flow problem has been dealt with considering power purchase from the market. A multi-objective optimization problem is formulated considering short-term power purchases from the power market. The cost function has two components viz generation cost and power purchase cost. Thus, under this scenario, the generation scheduling/OPF problem is an optimization problem of minimization of total cost of power to be generated by internal generators and to be purchased from the market (operating cost of power system).Apart from the cost, the other objective that we are looking to minimize here is emission. The offered prices for power is treated as fuzzy variables. DEMO (Differential Evolution for Multiobjective Optimization) as presented by Robic and Filipic in [9] is used to solve the optimal purchase planning problem formulated.

The proposed approach has been tested on modified IEEE 30-Bus system with 6 generators, where four generators are considered as utility generators and the remaining two as non-utility/market generators.

II. PROBLEM FORMULATION

The multi-objective economic/environmental optimal power purchase planning problem has been mathematically formulated as follows:

A. *Objective Function*

The objective of the given problem is to minimize both the total cost and the total emission. Thus the objective function can be represented as,

$$\min[F_1, F_2] \tag{1}$$

Where, F_1 and F_2 are total cost and total emission of generators respectively.

The total cost has two components viz., cost of power to be generated by internal generators (i.e., utility generators) and power purchase cost. Thus the same could be represented as,

$$F_1 = \sum_{i=1}^{Ng} C_i(P_{gi}) + C_{mr}(P_{mr}) \tag{2}$$

Where, C_i = Cost of active power generation (in \$/MW/hr) by i^th generator

C_{mr} = Cost of purchasing power form the market(in \$/MW/hr).

P_{gi} = Power output of i^th generator (MW)

P_{mr} = Power to be purchased from market (MW)

The cost of generated power (\$/hr) in terms of control variables viz generator powers can be expressed as,

$$C_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 \tag{3}$$

where a_i, b_i, c_i are the cost curve coefficients.

The total function of emission F_1 (kg/hr), can be expressed as,

$$\sum_{i}^{Ng} \alpha_i P_{gi}^2 + \beta_i P_{gi} + \gamma_i \tag{4}$$

where α_i , β_i and γ_i are emission coefficients of the i^th generator .

B. *Constraints*

The objective function is optimized with the following constraints.

Power Balance Constraint

Overall power balance equation for the network is:

$$(\sum_{i=1}^{Ng} P_{gi} + P_{mr}) - P_D - P_L = 0 \tag{5}$$

Where,

P_D = Load Demand (MW)

P_L = Transmission loss (MW)

N_g = Number of utility generators connected to the network.

Unity Capacity Constraint

These inequality constraints define the limits imposed on the active and reactive power production from generators due to the machine's design related limitations.

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\min} \tag{6}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\min} \tag{7}$$

where $P_{gi}^{\min}$ and $P_{gi}^{\max}$ are the lower and upper bounds on the active power output from the i_th generator, and $Q_{gi}^{\min}$ and $Q_{gi}^{\max}$ are the lower and upper bounds on the reactive power output from the i^th generator.

Security Constraint

$|P_l| \le P_{l\max}, l = 1,2,...,L$ where P_l is the power transmitted over line l . $P_{l\max}$ denotes the max limit of the transmissible power over line l . L is the total number of lines.

$$\sum_{i=1}^{Ng} S_{Ri} \ge S_R^{req} \tag{8}$$

$$\sum_{i=1}^{Ng} S_{Ri} \le P_{gi}^{\max} - P_{gi} \tag{9}$$

$$S_{Ri} \le S_{Ri}^{\max} \tag{10}$$

Where, S_{Ri} = spinning reserve capability of unit i

S_R^{req} = system spinning reserve requirement.

$S_{Ri}^{\max}$ =maximum spinning reserve capability of unit i

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad (11)$$

Where,

$V_i^{\min}$ = Lower voltage magnitude bounds for the ith bus.

$V_i^{\max}$ =Upper voltage magnitude bounds for the ith bus.

V_i = Voltage magnitude at bus i

III. DEMO: DIFFERENTIAL EVOLUTION FOR MULTI-OBJECTIVE OPTIMIZATION

In this paper, DEMO: Differential Evolution for Multi objective Optimization as presented by Robic and Filipic in [9] is used to solve the economic-emission dispatch problem formulated. DEMO is a variant of differential evolution (DE) [10]. Based on DE, DEMO builds on the success of Price's algorithm and adds the mechanisms of non-dominated sorting and crowding distance metric as used by state-of-the-art multi objective evolutionary algorithms. DEMO modifies the selection mechanism used to decide when a child replaces the parent. Details regarding the DEMO algorithm can be found in [9].

Pseudo-code for DEMO:

```
a) Evaluate the initial population $P$ of random individuals.
b) While stopping criterion not met, do:
c) For each individual $P_i$ (i =1, ..., popSize) from P repeat:
d) Create candidate C from parent. $P_i$
e) Evaluate the candidate.
f) If the candidate dominates the parent, the candidate replaces the parent. If the parent dominates the candidate, the candidate is discarded. Otherwise, the candidate is added in the population.
g) If the population has more than popSize individuals, truncate it.
h) Randomly enumerate the individuals in $P$ .
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The described DEMO's procedure is one of the three variants presented in [10]. It is called DEMO/parent and is the most elementary variant. Throughout this paper DEMO/parent is used. The key parameters of control are population size (N_P), scaling factor (F) and crossover constant (C_R).

IV. DEMO SOLUTION METHODOLOGY

In this paper DEMO is used to solve the multi-objective optimization problem defined by (1).As already mentioned, the total cost is the sum of cost of power to be generated by internal generators (i.e., utility generators) and power purchase cost. The cost of purchased power from the market being an uncertain variable is modeled as a triangular fuzzy number with linear functions for left and right membership. The minimum price is $\overline{\lambda} = \left(\lambda_0, l_{\lambda_0}, r_{\lambda_0}\right)$ and the offered price to import the maximum power is $\overline{\lambda_{\max}} = \left(\lambda_{\max}, l_{\lambda_{\max}}, r_{\lambda_{\max}}\right)$.The data related to λ_0 and λ are taken from [2].

The step-by-step algorithm of the proposed approach is as described below:

Step (1) Read the database for the generator data, bus data, transformer data and transmission line data.
Step (2) Assume suitable population size, maximum number of generations.
Step (3) Randomly generate the individuals.
Step (4) Run power flow using the Newton-Raphson method for each set of generating patterns P_{gi} corresponding to a particular generation and after that determine, slack bus generation, bus voltage magnitudes and phase angles at all the buses. Also calculate power flow in each transmission line of the system.
Step (5) Perform mutation and crossover for each target vector and create a trial vector.
Step (6) Perform selection for each target vector as mentioned in the pseudo code for DEMO, described in the previous section.
Step (7) Stop if the maximum number of generations is reached otherwise go to Step 4.
Step (8) After evaluating a series of generations ,the final pareto optimal solution set is generated and the best compromise solution is selected as the final solution .Store the total cost of generation ,emission and the generation pattern corresponding to the individual deemed best.

In practical operation, only one of the pareto-optimal solutions has to be used from the entire set generated by the algorithm. To avoid error due to imprecision of human judgment the methodology for determining best compromise solution by fuzzy set theory as employed in [11] has been made use of in this paper.

V. CASE STUDIES

The IEEE 30-bus system has been used to show the effectiveness of the proposed algorithm. The cost and emission coefficients' data used is given in Table VI. The emission from the market generators is ignored to preserve the decentralized nature of the solution algorithm.

In this work, generators connected to bus nos. 11 & 13 are considered as market generators and the remaining as utility generators. Voltage magnitude limits of generator buses are set to $0.95\,p.u. \le V \le 1.1\,p.u.$ and load buses are set to $0.95\,p.u. \le V \le 1.05\,p.u.$ .Voltage angle limits are taken as $-14 \le \delta \le 0$ in degree. The transmission line loadability limit for generator output paths is taken as 150MW and for the rest of the lines it is taken as 25MW. The total load of the IEEE 30-Bus network is 283.40 MW. Spinning reserve requirement is taken as 15% of the normal load on the system (i.e., 0.15*283.4 MW = 50 MW).The proposed algorithm has been implemented in MATLAB 2008b on a PC (Core2Duo, 2 GB, 2.5 GHz).

The Optimal power purchase problem is solved using DEMO. The population size (N_P), scaling factor (F) and crossover constant (C_R) have been selected as 200, 0.8 and 0.2 for system under consideration in the proposed DEMO algorithm. Results obtained from DEMO are compared with those obtained from NSGAII. The population size, crossover and mutation probabilities for NSGAII have been selected as 200, 0.9 and 0.2, respectively, for NSGAII. Maximum number of generations has been selected as 150 for both DEMO and NSGAII. To compare and evaluate the quality of the results 10 runs of each algorithm were performed. Total cost, emission, loss and CPU time obtained from DEMO and NSGAII are summarized in Table I. Only the results pertaining to the best of the 10 runs is highlighted. Table IV provides voltage magnitude and phase angle of all buses obtained from DEMO and NSGAII. The emission-cost trade-off curve for NSGAII and DEMO are shown in Fig. 1 and Fig 2 respectively. There are no line loadability limit violations. Spinning reserve requirements are also satisfied, with the utility generators carrying more reserves than the minimum required. Table III gives a summary of the spinning reserve requirement and allocation. Results shown in Table I, suggest that DEMO and NSGAII obtain nearly similar results with respect to total cost, emission and transmission loss. The relatively heavy computational cost of the DEMO approach is due to additional calculations, such as the DEMO specific election procedure. An analysis of the pareto fronts of NSGAII (Fig. 1) and DEMO (Fig. 2) reveals that NSGAII returns greater number of solutions belonging to the true pareto front and also has better spread of solution.

TABLE I
GENERATION, COST, EMISSION, LOSS AND CPU TIME OBTAINED FROM DEMO AND NSGAII

Particulars	**DEMO**	**NSGAII**
P_{G1}(MW)	125.5452	127.1718
P_{G2}(MW)	45.3000	45.9800
P_{G3}(MW)	23.5600	23.5400
P_{G4}(MW)	25.2700	23.1000
P_{G5}(MW)	30.0000	29.9900
P_{G6}(MW)	40.0000	40.0000
Total P_G(MW)	289.6752	289.7818
Cost($/hr)	743.2600	742.3100
Emission(Kg/hr)	228.9100	230.4000
Ploss(MW)	06.2752	06.3818
CPU Time(s)	757.0000	598.0000

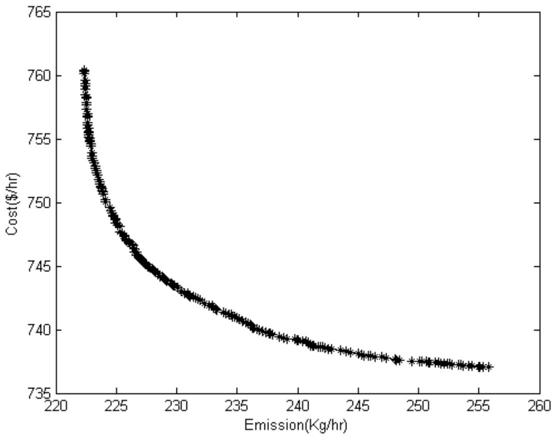

Fig. 1 Pareto Optimal Solutions obtained using NSGAII

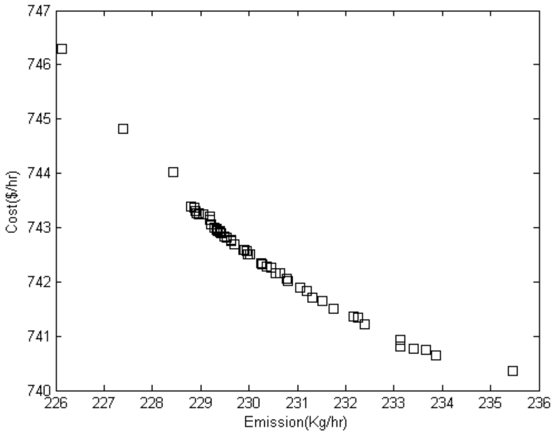

Fig. 2 Pareto Optimal Solutions obtained using DEMO

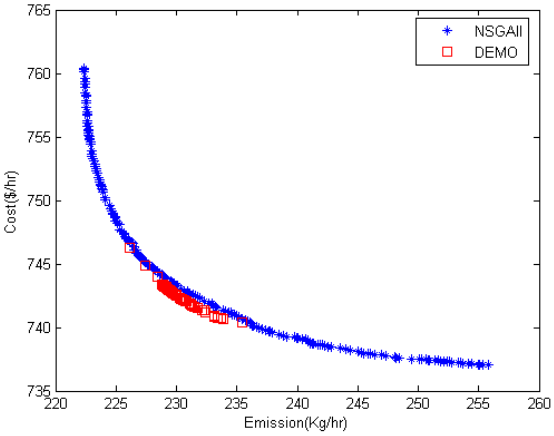

Fig. 3 Pareto Optimal Solutions obtained using NSGAII and DEMO represented on the same scale

However, in the stated problem the Decision Maker (DM) is interested in knowing trade-off optimal solutions in the intermediate cost and emission area. As is evident from Fig.3, the DEMO algorithm is able to find solution in the region of interest instead of finding solution on the entire pareto optimal front, thereby allowing the DM to consider only a set of solutions that lie on the regions of interest so that a better and more reliable decision can be made.

TABLE II
BUS VOLTAGE MAGNITUDE AND PHASE ANGLE OBTAINED FROM DEMO AND NSGAII

BusNo.	DEMO		NSGAII	
	Voltage Magnitude (p.u.)	**Phase Angle (degree)**	**Voltage Magnitude (p.u.)**	**Phase Angle (degree)**
1	1.0600	0.0000	1.0600	0.0000
2	1.0430	-2.5133	1.0430	-2.5446
3	1.0293	-3.6612	1.0293	-3.7290
4	1.0218	-4.3647	1.0218	-4.4473
5	1.0100	-8.3616	1.0100	-8.4316
6	1.0177	-5.2574	1.0177	-5.3664
7	1.0069	-7.0555	1.0068	-7.1486
8	1.0100	-5.3069	1.0100	-5.4637
9	1.0539	-5.5306	1.0539	-5.6365
10	1.0474	-7.3873	1.0474	-7.4912
11	1.0820	-2.3937	1.0820	-2.5006
12	1.0632	-5.8212	1.0632	-5.9148
13	1.0710	-3.0024	1.0710	-3.0959
14	1.0483	-6.8313	1.0483	-6.9263
15	1.0426	-7.0453	1.0426	-7.1417
16	1.0491	-6.7480	1.0491	-6.8458
17	1.0425	-7.3996	1.0425	-7.5017
18	1.0321	-7.8540	1.0321	-7.9531
19	1.0291	-8.1462	1.0291	-8.2468
20	1.0329	-8.0139	1.0328	-8.1153
21	1.0352	-7.8593	1.0352	-7.9632
22	1.0358	-7.8552	1.0358	-7.9592
23	1.0312	-7.7516	1.0311	-7.8513
24	1.0245	-8.3600	1.0245	-8.4642
25	1.0198	-8.7522	1.0198	-8.8623
26	1.0022	-9.1698	1.0021	-9.2799
27	1.0257	-8.7378	1.0257	-8.8516
28	1.0151	-5.6625	1.0151	-5.7816
29	1.0059	-9.9617	1.0059	-10.0756
30	0.9945	-10.8401	0.9944	-10.9541

TABLE III
SPINNING RESERVE DATA

Gener-ator	**Max Spinning reserve capability (MW)**	**Available reserve(MW) DEMO**	**Available reserve(MW) NSGAII**
P_{G1}	30.00	s74.4548	70.6365
P_{G2}	10.00	34.7000	37.9900
P_{G3}	05.00	26.4400	26.0900
P_{G4}	05.00	09.7300	10.5000

The difference between the best and the worst cost solution for multiple (ten) runs of the program is very less in case of both DEMO (0.17 %)) and NSGAII (0.08%) as illustrated in Table IV, which shows the consistency in the results.

TABLE IV
BEST AND WORST RESULTS FOR DEMO AND NSGAII

Particul-ars	**Best Solution**		**Worst Solution**		**%Difference**	
	Cost ($/hr)	Emission (Kg/hr)	Cost ($/hr)	Emission (Kg/hr)	Cost ($/hr)	Emission (Kg/hr)
DEMO	743.26	228.91	744.52	230.90	0.17	0.87
NSGAII	742.33	230.38	742.99	230.90	0.08	0.23

For the purpose of fair comparison, the data presented in Table I is obtained with the market price held constant at 2.46$/MWhr for both DEMO and NSGAII. As is evident from the value of power drawn for the market generators, the offered price being less, the market generators are getting loaded at the upper limits of their operational range.

To confirm the efficacy of the algorithm in generating proper purchase plan, the algorithm has also been run with the offered price held at an arbitrary value of 20$/MWhr. The results as presented in Table V, highlight the fact that with Load Scaling Factor (LSF)=1.0, the power drawn from the market generators is lesser as compared to the power drawn when the offered price is 2.46$/MWhr. Also, the results for LSF=1.3 reveal that with the increase in load, the power drawn from the market generator increases irrespective of the price in-order-to maintain system stability. This shift in the optimal operating point with changing values of offered price and LSF indicates the capability of the algorithm to generate a good dispatch and power purchase plan.

TABLE V
GENERATION AND COST FOR OFFERED PRICE=$20/MWHR

LSF	**1.0**	**1.3**
P_{G1}(MW)	130.7863	200.0000
P_{G2}(MW)	56.7300	50.1000
P_{G3}(MW)	38.2000	33.0800
P_{G4}(MW)	35.0000	33.7700
P_{G5}(MW)	15.2700	25.1800
P_{G6}(MW)	13.6400	27.6100
Cost($/hr)	1312.76	1700.05

TABLE VI
GENERATOR COST AND EMISSION COEFFICIENTS

Generator N_G	N_1	N_2	N_3	N_4	N_5	N_6
a_i	0.00375	0.01750	0.06250	0.00834	Market Generator	
b_i	2.00	1.75	1.00	3.25		
c_i	0.0	0.0	0.0	0.0		
α_i	0.0126	0.0200	0.0270	0.0291		
β_i	-1.1000	-0.1000	-0.0100	-0.0050		
γ_i	22.983	25.313	25.505	24.900		
P_{min}	50	20	15	10		
P_{max}	200	80	50	35		

VI. CONCLUSION

This paper focuses on generating an optimal power purchase schedule so as to minimize total cost and total emission, considering power purchases from the market. DEMO is successfully implemented to solve the problem. The results establish the feasibility of such an approach and highlight the benefits gained, such as, saving in total system cost and reduction in emission as a result of strategic drawal. In this paper, DEMO is used in resolving the proposed example and the same is compared vis-à-vis NSGAII. DEMO achieves similar solution as NSGAII on the modified IEEE 30-bus system. However, in case of DEMO most of the pareto-optimal solutions lie in the intermediate trade-off region where-in the best compromise solution is supposed to reside and hence this algorithm can be considered to be more precise in its approach. This high convergence precision helps to make a good power purchase plan. DEMO's only disadvantage over NSGAII is its higher computational time due to the computational complexity involved.

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