Dynamic Economic/Environmental Dispatch Problem Considering Prohibited Operating Zones

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Abstract—**Along with economic dispatch, emission dispatch has become a key problem under market conditions. Thus, the combination of the above problems in one problem called economic emission dispatch (EED) problem became inevitable. However, due to the dynamic nature of today's network loads, it is required to schedule the thermal unit outputs in real-time according to the variation of power demands during a certain time period. Within this context, this paper presents an elitist technique, the second version of the non-dominated sorting genetic algorithm (NSAGII) for solving the dynamic economic emission dispatch (DEED) problem. Several equality and inequality constraints, such as valve point loading effects, ramp rate limits and prohibited operating zones (POZ), are taken into account. Therefore, the DEED problem is considered as a non-convex optimization problem with multiple local minima with higher-order non-linearities and discontinuities. A fuzzy-based membership function value assignment method is suggested to provide the best compromise solution from the Pareto front. The effectiveness of the proposed approach is verified on the standard power system with ten thermal units.**

Keywords-dynamic environmental/economic dispatch; prohibited operating zones; multi-objective optimization; non-dominated sorting genetic algorithm

I. INTRODUCTION

In electric power systems, improvement of operation and planning has become more important under the current market conditions and several tools have been developed in this context [1, 2]. Economic load dispatch (ED) is one of them. It aims to schedule the outputs of the committed generating units so as to minimize the total fuel cost under specific system equality and inequality constraints. This objective can no longer be considered alone due to severe environmental standards imposed by legislations. In this respect, the Clean Air Act Amendments have been applied in the USA to reduce pollution and atmospheric emissions such as sulfur oxides, SO_X, and nitrogen oxides, NO_X, caused by fossil-fueled thermal units [3, 4]. Hence, improvements in dispatching electric power must consider both monetary profits and reduced emissions of gaseous pollution. Thus, we are facing a bi-objective minimization problem, which has been frequently known as the static environmental/economic dispatch (SEED) problem. SEED can only handle a single loading condition at a particular time instant [3-8]. Due to the large variation of the load demand and dynamic nature of the power systems in recent years, it is mandatory to schedule the generator outputs in real time according to the variation of power demands over a certain time period. There are several formulations of this problem, known as the dynamic environmental/economic dispatch (DEED) problem [9-12]. Generally, DEED is a dynamic optimization problem having the same objectives as SEED over a time period subdivided into smaller time intervals with respect to the constraints imposed on system operation by generator ramp-rate limits. Time period and time intervals can be one day and one hour, respectively. Therefore, the operational decision at an hour may affect the operational decision at a later hour. Authors in [11-16] summarize several techniques for solving dispatch problems. Conventional methods, such as dynamic programming, nonlinear programming, network flow method, and interior point method [16] have been criticized as they are iterative, sensitive to initial solution and converge into local optimum solution. To overcome these difficulties, more recent works centered around artificial intelligence (AI), such as genetic algorithm [17], Tabu search [18], particle swarm optimization [19-20], simulated annealing [12], differential evolution [13] and bacterial

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foraging [14]. These techniques proved to have a clear edge over traditional methods in solving DEED problems without any or less restrictions on the shape of the objective functions curves where multiple Pareto-optimal solutions can be obtained in a single run. Most of the past studies have only focused on the SEED problem except for a few where the multi-objective DEED problem is considered [14]. In [14], prohibited operating zones, ramp rate limit constraints and valve point loading effects (VPLE) have been considered. Therefore, the DEED becomes highly nonlinear and with discontinuous and non-convex cost functions.

Within this context, this paper presents an elitist multi-objective approach for solving the DEED problem including POZ, valve point loading effects, and ramp rate limit constraints. This proposed method, called second version of the non-dominated sorting genetic algorithm (NSAGII), incorporates a crowding distance comparison at the end of each iteration in order to facilitate the convergence of the optimization algorithm to the real Pareto optimal front. In general terms, the contribution of this study is to show that the NSGA approach used frequently for solving continuous problems can be efficient for non-smooth and non-convex DEED problems if a non-domination sorting technique is incorporated in the optimization algorithm. In addition, the ramp rate limit constraints have been considered during transition from the last hour of a day to the first hour of the next. A fuzzy set theory [5] is used to extract the best compromise solution from the Pareto optimal front for the decision makers. The proposed approach was tested on a ten-unit test system incorporating all above constraints. This approach showed a very competitive performance when compared with the original NSGA algorithm.

II. PROBLEM FORMULATION

The DEED problem is considered as a multi-objective problem (MOP). It aims to minimize simultaneously the total fuel cost and total emission of thermal units over a certain period of time subdivided into smaller time intervals. Several equality and inequality constraints are considered in the problem formulation. Considering a power system with N generators, the total fuel cost function C_T in (\$/h) including VPLE and emission in (ton/h) are, respectively described by (1) and (2) [20]:

$$C_T = \sum_{t=1}^{T} \sum_{i=1}^{N} \left[a_i + b_i P_i^t + c_i \left(P_i^t \right)^2 + \left| d_i \sin\left\{ e_i \left(P_i^{\min} - P_i^t \right) \right\} \right| \right] \quad (1)$$

$$E_T = \sum_{t=1}^{T} \sum_{i=1}^{N} \left[10^{-2} \left(\alpha_i + \beta_i P_i^t + \gamma_i \left(P_i^t \right)^2 \right) + \eta_i \exp\left(\lambda_i P_i^t \right) \right] \quad (2)$$

where, P_i^t is real power output of the i-th unit at time t. T is the number of hours. a_i , b_i , c_i , d_i and e_i are the cost coefficients of the i-th unit. α_i , β_i , γ_i , η_i and λ_i are the emission coefficients of the i-th unit. Objective functions C_T and E_T are optimized subject to the constraints described below.

A. Generation Limits

$$P_i^{\min} \le P_i^t \le P_i^{\max}, \; i = 1,...,N \quad (3)$$

B. Power Balance Constraints

Total demand power P_D^t and total losses P_L^t must be covered at each interval of time *t*.

$$\sum_{i=1}^{N} P_i^t - P_D^t - P_L^t = 0, \; t = 1,...,T \quad (4)$$

In this study, total losses are expressed as follows [20]:

$$P_L^t = \sum_{i=1}^{N} \sum_{j=1}^{N} P_i^t B_{ij} P_j^t + \sum_{i=1}^{N} B_{oi} P_i^t + B_{oo} \quad (5)$$

where B_{ij} , B_{oi} , B_{oo} are called *B* coefficients.

C. Ramp Rate Limits

$$P_i^{t-1} - P_i^t \le R_i^{down} \quad (6)$$

$$P_i^t - P_i^{t-1} \le R_i^{up} \quad (7)$$

where R_i^{down} and R_i^{up} are the down and up rate limits of the i-th unit, respectively.

D. Constraints Due to Prohibited Operating Zones

$$P_i^t \in \begin{cases} P_i^{\min} \le P_i^t \le \underline{P}_i^1 \\ \overline{P}_i^{k-1} \le P_i^t \le \underline{P}_i^k, k = 2,...,z_i \\ \overline{P}_i^{z_i} \le P_i^t \le P_i^{\max} \end{cases} \quad (8)$$

where z_i is the number of prohibited operating zones for the i-th unit, and $\overline{P}_i^k$ and $\underline{P}_i^k$ are upper and lower bounds of the prohibited zone number *k*.

III. IMPLEMENTATION OF THE PROPOSED METHOD

Multi-objective evolutionary algorithms using non-dominated sorting and sharing, such as NSGA and NPGA, have been criticized for the absence of elitism. Therefore, the second version of NSGA, called NSGAII [21] is utilized in this study for solving the DEED problem. In this approach, the sharing function approach is replaced with a crowded comparison. Initially, an offspring population Q_t is created from the parent population P_t at the t-th generation. Then, a combined population R_t is formed:

$$R_t = P_t \cup Q_t \quad (9)$$

R_t is sorted into different no-domination levels F_j. So, we can write:

$$R_t = \cup_{j=1}^{r} \left(F_j \right) \quad (10)$$

where, r is the number of fronts. To offer a higher precision with reduced CPU time, this algorithm has been implemented using real-coded genetic algorithm in [5, 19].

IV. RESULTS AND SIMULATION

The effectiveness of the proposed optimization algorithm for solving the DEED problem is assessed on the 10-unit system. All system data are taken from [14, 20]. The B-loss coefficients are given below.

$$B = 10^{-4}\begin{bmatrix} 0.49 & 0.14 & 0.15 & 0.15 & 0.16 & 0.17 & 0.17 & 0.18 & 0.19 & 0.20 \\ 0.14 & 0.45 & 0.16 & 0.16 & 0.17 & 0.15 & 0.15 & 0.16 & 0.18 & 0.18 \\ 0.15 & 0.16 & 0.39 & 0.10 & 0.12 & 0.12 & 0.14 & 0.14 & 0.16 & 0.16 \\ 0.15 & 0.16 & 0.10 & 0.40 & 0.14 & 0.10 & 0.11 & 0.12 & 0.14 & 0.15 \\ 0.16 & 0.17 & 0.12 & 0.14 & 0.35 & 0.11 & 0.13 & 0.13 & 0.15 & 0.16 \\ 0.17 & 0.15 & 0.12 & 0.10 & 0.11 & 0.36 & 0.12 & 0.12 & 0.14 & 0.15 \\ 0.17 & 0.15 & 0.14 & 0.11 & 0.13 & 0.12 & 0.38 & 0.16 & 0.16 & 0.18 \\ 0.18 & 0.16 & 0.14 & 0.12 & 0.13 & 0.12 & 0.16 & 0.40 & 0.15 & 0.16 \\ 0.19 & 0.18 & 0.16 & 0.14 & 0.15 & 0.14 & 0.16 & 0.15 & 0.42 & 0.19 \\ 0.20 & 0.18 & 0.16 & 0.15 & 0.16 & 0.15 & 0.18 & 0.16 & 0.19 & 0.44 \end{bmatrix} \quad (11)$$

The NSGAII algorithm is implemented in MATLAB R2009a on a 64-bit operating system on a PC with an Intel i3-2370M CPU at 2.40GHz. The best compromise solution is generated from the Pareto front using a fuzzy based membership function value assignment method [5]. The NSGAII parameters to find the best Pareto set for the SEED problem have been chosen by trial and error and they were used for the DEED problem. In this study, the maximum number of generations and the population size were both chosen to be 200.

- Test case 1: The SEED problem for the ten-unit system with P_D=1036MW was considered in this case. Optimal outputs of thermal units for best cost, best emission and best compromise solution have been computed using the proposed optimization algorithm. Results have been compared with those obtained using NSGA.
- Test case 2: The DEED for the test system over a 24-hour time horizon was solved under all previous constraints. POZ limits in MW shown in Table I are taken from [22]. Therefore the problem will be more complicated with discontinuities. The hourly variation of the load is depicted in Figure 1.

TABLE I. UNIT OPERATING LIMITS IN MW

Unit	$P_i^{\min}$	$P_i^{\max}$	R_i^{down}	R_i^{up}	Prohibited zone
1	150	470	80	80	[150 165], [448 453]
2	135	470	80	80	[90 110], [240 250]
3	73	340	80	80	-
4	60	300	50	50	-
5	73	243	50	50	-
6	57	160	50	50	-
7	20	130	30	30	-
8	47	120	30	30	[20 30], [40 45]
9	20	80	30	30	-
10	10	55	30	30	[12 17], [35 45]

A. SEED Problem: Test Case 1

For the validation of the proposed algorithm, a comparison with the first version of NSGA is suggested in this case. From Figure 1, it is clear that NSGAII provides the best results and it has better diversity characteristics of non-dominated solutions. From Table II, the minimum fuel cost and emission provided by NSGAII are $61,775.44 and 3,785.47lb respectively. Moreover, the highest value of the fuel cost is found for minimum emission and the highest value of the emission corresponds to the minimum fuel cost since they are conflicting objective functions.

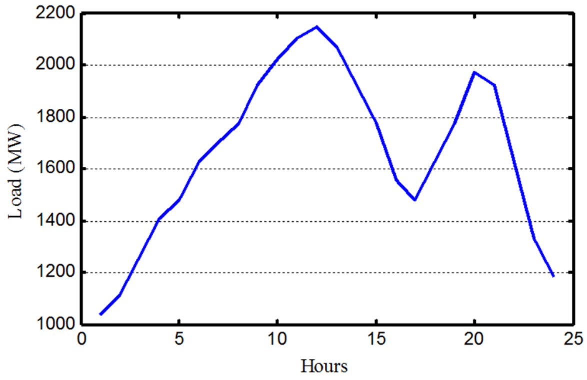

Fig. 1. Hourly load variation

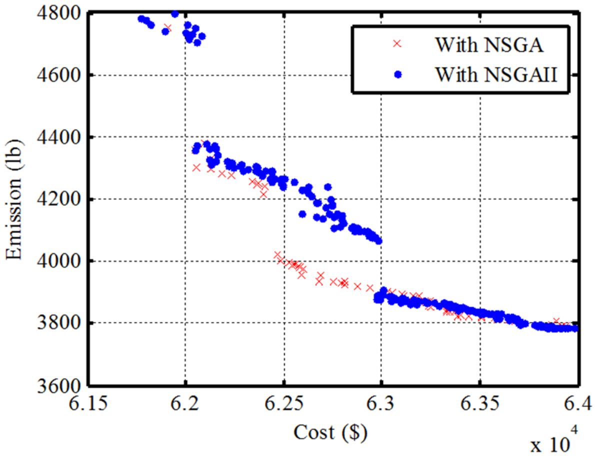

Fig. 2. Pareto solutions with NSGAII and NSGA (case 1)

B. DEED Problem Considering All Constraints: Test Case 2

In this case, the generation output of unit at each hour has been adjusted considering POZ. Consequently, discontinuities are introduced in cost and emission curves corresponding to the POZ. The hourly evolution of the optimum generations using the proposed algorithm for minimum cost is shown in Figure 3. It is clear that the outputs of all units are maximum at hour 12 which corresponds to the maximum load (2150MW). In this sub-section, optimum solution for minimum emission is not displayed due to the space limitation. Table III shows the compromise solution extracted from the Pareto solutions. It is clear that the proposed scheduling of generations satisfies all previous constraints.

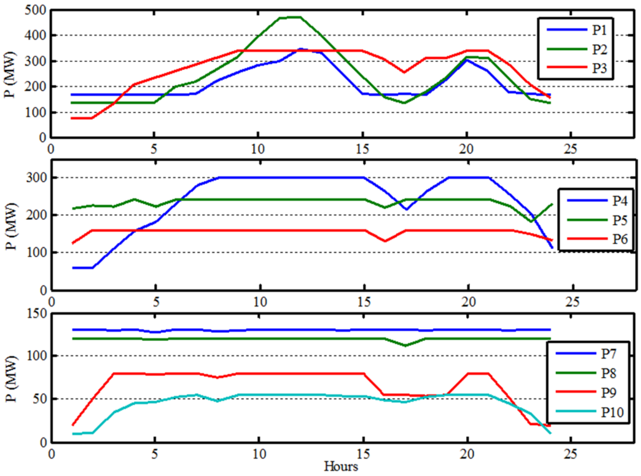

Fig. 3. Hourly evolution of the optimum solution for minimum cost

V. CONCLUSION

The DEED problem is one of the most crucial issues to be solved in the power system field. It has a great importance in reducing emission of harmful gases and saving energy. In this study, the DEED problem has been formulated as a bi-objective optimization problem with nonlinear constraints including VPLE, ramp rate limits and prohibited operating zones. The second version of the non-dominated sorting genetic algorithm (NSGAII) has been suggested for solving the DEED problem for 24-hour dispatch intervals. To demonstrate the effectiveness of the proposed approach, the standard power system with ten thermal units was used. Various cases with different levels of complexity and discontinuity have been considered. The results of the proposed approach are significantly improved when compared with NSGA. In addition, this approach has the capacity to optimize any number of objective functions simultaneously and generate the Pareto front in a single run. Therefore, other objectives can be included in the main problem such as voltage drop and real power losses.

TABLE II. OPTIMUM SOLUTIONS FOR CASE 1

	Minimum fuel cost		**Minimum emission**		**Best compromise solution**	
Method	**NSAGII**	**NSGA**	**NSGAII**	**NSGA**	**NSGAII**	**NSGA**
P1	165.657	165.304	165.465	165.277	165.092	165.400
P2	135.000	135.000	136.471	138.754	135.000	135.073
P3	73.0000	73.0000	85.943	89.8068	78.3817	73.0000
P4	60.0000	60.0000	87.8645	88.9776	85.9374	77.8433
P5	221.551	224.103	135.325	124.263	123.237	131.320
P6	120.835	118.647	126.733	126.764	128.576	124.444
P7	130.000	130.000	91.4739	97.8403	129.019	130.000
P8	120.000	120.000	91.9147	89.3054	84.4827	120.000
P9	20.0000	20.0000	79.6906	79.8941	79.5035	51.7425
P10	10.0000	10.0000	55	55.0000	46.6442	47.0783
Cost ($/h)	61775.4	61802.6	63914.4	63905.5	62974.5	62486.2
Emission (lb/h)	4781.79	4800.55	3785.47	3785.51	3880.30	3998.43

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TABLE III. BEST COMPROMISE SOLUTION OF DEED FOR TEST CASE 2

Hour	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**
1	165.0185	136.1190	73.0000	88.1843	125.1063	121.1142	130.0000	119.4657	52.5923	45.2700
2	165.1026	135.1579	81.5542	108.405	173.2150	122.5238	100.0000	120.0000	80.0000	46.7179
3	165.0594	135.7696	130.6567	127.3521	183.7788	159.8147	129.6961	120.0000	80.0000	54.5710
4	165.5635	182.8389	164.0515	160.2915	225.3338	159.3824	130.0000	119.8330	79.8469	54.9029
5	165.4107	202.1567	185.8223	182.477	240.2090	159.8194	129.8451	119.7818	79.8544	54.6686
6	205.1453	218.9835	245.006	228.7587	243.0000	160.0000	121.126	120.0000	80.0000	55.0000
7	200.0936	220.9863	294.5041	278.7587	243.0000	160.0000	106.1606	120.0000	77.1945	55.0000
8	232.4056	297.4300	259.7886	263.0712	243.0000	157.1222	127.8133	120.0000	80.0000	55.0000
9	295.7609	309.5763	339.7886	263.2257	241.7996	160.0000	130.0000	120.0000	80.0000	55.0000
10	317.6374	355.8988	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
11	358.3159	412.7551	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	74.8769	55.0000
12	379.7618	434.7244	339.9887	299.9990	242.9959	160.0000	129.9935	119.9976	80.0000	54.9757
13	346.8023	381.7131	340.0000	299.9520	242.9962	159.9909	130.0000	119.977	79.9899	55.0000
14	302.4077	308.1888	300.5633	295.9688	243.0000	160.0000	130.0000	119.9821	80.0000	55.0000
15	228.2163	264.2944	285.2806	270.8877	243.0000	159.4424	129.6214	119.887	79.9751	54.5439
16	165.3236	222.6713	209.3282	239.4035	243.0000	159.4886	129.903	120.0000	54.6538	54.5022
17	165.1747	216.9418	186.1643	189.4035	242.8615	159.9508	129.8344	119.8230	55.0000	55.0000
18	226.6097	223.5607	229.9497	234.5908	242.8186	160.0000	130.0000	119.9758	55.0000	54.7545
19	239.3959	299.4056	276.9271	258.0446	242.9016	159.8063	129.7669	119.8321	54.7896	54.8522
20	276.0364	342.8300	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
21	302.8172	308.8301	298.5865	298.2182	242.3453	159.9713	129.7167	119.7893	80.0000	54.8529
22	224.9485	228.8301	218.5865	258.7530	209.6452	160.0000	130.0000	120.0000	80.0000	46.5327
23	165.4124	149.0684	141.616	209.7076	166.2512	157.8307	128.9253	119.6998	79.8154	45.7563
24	165.5672	135.0000	73.0000	138.1843	175.1063	145.5599	123.5542	120.0000	80.0000	53.6633
Total cost ($)	2526555.7207									
Total emission (lb)	302900.8703									
Total losses (MW)	1301.8534									

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