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Hybrid DE-SQP for solving dynamic economic emission dispatch with prohibited operating zones

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Abstract. This paper proposes a hybrid differential evolution and sequential quadratic programming (DE-SQP) for solving dynamic economic emission dispatch (DEED) problems with prohibited operation zones and transmission line losses. The DEED is a non-convex multi-objective optimization problem where both fuel cost and emission are simultaneously minimized under a set of constraints. The DE is applied to find a near global solution and SQP is used as a local search to determine the optimal solution at the final. To illustrate the effectiveness of the DE-SQP approach, a five-unit test system is used. The results show the effectiveness and the superiority of the proposed method over other methods.

1 INTRODUCTION

Dynamic economic dispatch (DED) results to great economic benefits in power system operation. The objective of the DED is to minimize the fuel cost over a time horizon under ramp rate constraints and other constraints (see e.g. [1]-[9]). The emission of pollutants like SO_2, NO_x, CO and CO_2 etc. that are produced from thermal power plants has to be consider in the DED problem. This can be done by formulating the following problems: (i) pure dynamic emission dispatch (PDED) [10] with the objective is to minimize the emission instead of fuel cost, under the same set of constraints given in the DED problem. (ii) dynamic economic emission dispatch (DEED) which minimizes simultaneously both emission and fuel cost under the ramp rate constraint and other constraints. (iii) emission constrained dynamic economic dispatch (ECDED) where the with the objective is to minimize fuel cost and consider the emission as a constraint in addition to the ramp rate constraint and other constraints. In the present paper we consider the DEED problem.

Generating units may have certain prohibited operating zones (POZs) due to faults in the machines themselves or instability concerns or the valve point effect. Hence, considering the effect of valve-points and POZs in generators' cost function, makes the economic dispatch a non-convex and non-smooth optimization problem.

Applications of the mathematical programming approaches such as the Gradient-based Algorithms are not suitable for solving this problem. Instead, several meta-heuristic optimization methods have been presented to solve this problem (see [11-16]). In [11]-[13] the static economic dispatch problem with prohibited operating zones has been solved. A number of reported works has considered the prohibited operating zones in DED problem (see e.g. [14]-[16]), however, the emission has not considered in these papers.

Differential evolution algorithm (DE), which is proposed by Price and Storn [17], is one of meta-heuristic optimization methods which can solve optimization problems with non-convex and non-smooth objective functions. DE has been used to solve the DED with valve point effects in [18]-[20]. DE often suffers the problem of premature convergence and long computation time to get optimal solution. Therefore, in [6] a hybrid differential evolution and sequential quadratic programming (DE-SQP) has been utilized to solve the DEED problem with valve-point effects. However, prohibited operating zones have not considered.

The aim of this paper is propose a hybrid DE-SQP for solving the DEED with valve-point effects and prohibited operating zones. The DE is used to find a near global solution and SQP is used as a local search to determine the optimal solution at the final.

2 FORMULATION OF THE DEED PROBLEM

In this section we introduce the DEED formulation. Assume that n is the number of committed units, P_i^t is the generation of unit i during the t-th time interval $[t-1,t)$; $C_i(P_i^t)$ and $E_i(P_i^t)$ are the generation cost and the amount of emission for unit i to produce P_i^t; D^t is the demand at time t (i.e., the t-th time interval); UR_i and DR_i are the maximum ramp up/down rates for unit i; $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum capacity of unit i respectively.

The total fuel cost and pollutants emission over the dispatch period [0,N] are given, respectively, by :

$$C = \sum_{t=1}^{N}\sum_{i=1}^{n} C_i(P_i^t),$$

$$E = \sum_{t=1}^{N}\sum_{i=1}^{n} E_i(P_i^t).$$

The DEED can be formulated as follows:

$$\min H = \omega C + (1-\omega)E \qquad (1)$$

satisfying the following constraints:

(i) Power balance constraint

$$\sum_{i=1}^{n} P_i^t = D^t + Loss^t, \qquad t = 1,2,...,N, \qquad (2)$$

where $Loss^t = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i^t B_{ij} P_j^t, \qquad t = 1,2,...,N,$

where B_{ij} is the ij-th element of the loss coefficient square matrix of size n

(ii) Generation limits

$$P_i^{\min} \le P_i^t \le P_i^{\max}$$
$$i = 1,2,...,n, \; t = 1,2,...,N, \qquad (3)$$

(iii) Generating unit ramp rate limits

$$-T \bullet DR_i \le P_i^{t+1} - P_i^t \le T \bullet UR_i$$
$$i = 1,2,...,n, \; t = 1,2,...,N-1, \qquad (4)$$

(iv) Prohibited operation zones limits (POZs):

Thermal generating units may have prohibited operation zones (POZs) due to the physical on component of units. Consequently, the whole operating region of a generating unit with prohibited operation zones will be broken into several isolated feasible sub regions. The allowable feasible sub regions of generation unit can be defined as:

$$P_i^t = \begin{cases} P_i^{\min} \le P_i^t \le P^l_{i,1} \\ P^u_{i,j-1} \le P_i^t \le P^l_{i,j}, \; j = 2,3,...,M_i, i = 1,2,.. \\ P^u_{i,M_i} \le P_i^t \le P_i^{\max} \qquad .,n, \; t = 1,2,...,N \end{cases} \qquad (5)$$

where $P^l_{i,j}$ and $P^u_{i,j}$ are the lower and upper limits of the j-th prohibited zones of unit i respectively. M_i is the number of prohibited operating zones of unit i and $\omega \in [0,1]$ is a weighting factor.

Note that if w=1, then problem (1) leads to the DED problem minimize the fuel cost regardless of emission. If w=0, then problem (1) leads to the PDED problem which minimize the emission regardless of cost [10].

In this paper we consider the following cost and emission functions:

$$C_i(P_i^t) = a_i(P_i^t)^2 + b_i P_i^t + c_i + \left| e_i \sin(f_i(P_i^{\min} - P_i^t)) \right|,$$

$$E_i(P_i^t) = \alpha_i(P_i^t)^2 + \beta_i P_i^t + \gamma_i + \eta_i \exp(\delta_i P_i^t),$$

where a_i, b_i, c_i, e_i and f_i are the fuel cost coefficients of generator i and they are constants. Constants $\alpha_i, \beta_i, \gamma_i, \eta_i$ and δ_i are the coefficient of the i-th unit emission characteristics.

3 Differential evolution method

DE is a meta-heuristic optimization method for solving non-convex optimization problem. The DE algorithm is a population based algorithm using three operators; mutation, crossover and selection to evolve from randomly generated initial population to final individual solution. Mutation and crossover are used to generate new vectors (trial vectors), and selection then determines which of the vectors will survive to the next generation. DE algorithm contains three control parameters, the differentiation (or mutation) constant F, crossover constant CR, and size of population NP. Assume that D is the diminution of the optimization problem; GEN is maximum number of generations (or iterations). The initialization population (parents) $X_i = \{x_{1i}, x_{2i}, ..., x_{Di}\}$ is randomly between the upper and lower bounds. Let $X_i^G = \{x^G_{1i}, x^G_{2i}, ..., x^G_{Di}\}$ be the individual i at the current generation G. A mutant vector $V_i^G = \{v^G_{1i}, v^G_{2i}, ..., v^G_{Di}\}$ is generated according to:

$$V_i^{G+1} = X_{r_1}^G + F \times (X_{r_2}^G - X_{r_3}^G), \; r_1 \ne r_2 \ne r_3 \ne i \qquad i = 1,2,...,NP \qquad (6)$$

where $r_1, r_2, r_3 \in \{1,2,...,NP\}$ are randomly chosen integers indexes and F is the mutant factor.

In order to increase the diversity of the perturbed parameter vectors, crossover is introduced. According to the target vector X_i^G and the mutant vector V_i^{G+1}, a new trial vector (offspring) $U_i^{G+1} = \{u^{G+1}_{1i}, u^{G+1}_{2i}, ..., u^{G+1}_{Di}\}$ is generated with

$$U_{ji}^{G+1} = \begin{cases} v_{ji}^G & \text{if}\,(\text{rand}(j) \le CR) \; or j = rnb(i) \\ x_{ji}^G & \text{otherwise} \end{cases} \qquad (7)$$

where $j = 1,2,..., D, i = 1,2,..., NP$ and $\text{rand}(j)$ is the jth evaluation of a uniform random between [0,1]. CR is the crossover constant. $rnb(j)$ is a randomly chosen index from $j = 1,2,..., D.$

The last strategy of DE algorithm is the selection process which determine the vectors will be chosen for the next generation by implementing one-to-one competition between the new generated trial vectors and their corresponding parents as follows as :

$$X_i^{G+1} = \begin{cases} U_i^{G+1} & \text{if } f(U_i^{G+1}) \le f(X_i^G) \\ X_i^G & \text{otherwise} \end{cases} \qquad i = 1,2,..,NP \qquad (8)$$

where f is the function to be minimized. From E.q. (8), one can see that, the value of function f of each trial vector U_i^{G+1} is compared with that of its parent target vector X_i^G. The above steps of reproduction and selection are repeated generation after generation until some stopping criteria are satisfied.

To evaluate the fitness of each individual in the swarm as we use the following evaluation function $f = H + \lambda \sum_{t=1}^{N} \left(\sum_{i=1}^{n} P_i^t - (D^t + Loss^t) \right)^2$ (9)

where λ is a penalty value. Then we aim to find the minimum evaluation value of all the individuals in all iterations where all the upper and lower capacity limits as well as the ramp rate limits are satisfied. The equality constraints are satisfied once the function f reaches its minimum.

4 Sequential quadratic programming

SQP method is one of the best iterative methods for solving nonlinear programs, i.e. mathematical optimization problems with nonlinear constraints. It is appropriate for small and large problems and it is well-suited to solving problems with significant nonlinearities. The method can be viewed as a generalization of Newton's method for unconstrained or constrained optimization. At each iteration, Broyden--Fletcher--Goldfarb--Shanno (BFGS) quasi-Newton updating method is used to approximate the Hessian of the Lagrangian function [21]. The SQP method solve a sequence of quadratic programming (QP) sub-problem defined in terms of a quadratic model of the objective function and a linearization of the constraints. More details about the SQP method can be found in [6].

5 SIMULATION RESULTS

In this section we present a test system consisting of five units with valve point effects and prohibited operating zones to investigate the effectiveness of the hybrid DE-SQP method. We solve the DEED problem with the values $\omega = 1$, $\omega = 0.5$ and $\omega = 0$. The technical data of the units, as well as the demand are taken from ([14], [22] and [23]) and are given in Tables 5 and 6 in Appendix. In the DE-SQP algorithm, the control parameters of the DE chosen as: population size NP = 60; max generation GEN = 20000; F = 0:423; CR = 0.885 and the results represent the average of 30 runs of the proposed method. MATLAB program has been used in all computations. The optimal solutions of the DED, DEED and PDED are given by Tables 1, 2 and 3, respectively. Table 1 shows hourly generation schedule, cost and emission obtained from DED problem. Table 3 shows hourly generation schedule, cost and emission obtained from PDED problem. It is seen from Tables 1 and 3 that the cost is 45590$ under DED but it increases to 52611$ under PDED and emission obtained from DED is 23567lb but decreases to 18955lb under PDED. Table 2 shows hourly generation schedule, cost and emission obtained from DEED problem. It can be seen that the cost is 46625$ which is more than 45590$ and less than 52611$, and emission is 20527lb which is less 23567lb and more than 18955lb.
Table 4 show that, the efficiency of DE-SQP method compare with other methods for DEED problems without consider the prohibited operating zones which obtained in our Ref. [6]. From the last row in Tables 1-3, one can see that, the effect of the prohibited operating zones constraint which makes the value objective function of DEED problem greater than the value in the last row in Table 4 for DEED problems.

H	P_1	P_2	P_3	P_4	P_5	$Loss$
1	22.3996	98.6207	112.8084	40.0000	139.8031	3.6319
2	42.9781	98.6046	112.7170	45.0000	139.7352	4.0349
3	22.9782	98.8819	112.8828	95.0000	150.0000	4.7429
4	10.0000	90.0137	111.3855	124.5782	200.0000	5.9775
5	10.0000	90.0002	110.9311	124.6576	229.1033	6.6922
6	40.0000	108.1170	113.1122	124.9853	229.6700	7.8845
7	33.7025	98.4619	112.6812	159.9997	229.4952	8.3405
8	11.8603	99.0099	113.0016	209.9132	229.4761	9.2611
9	10.0045	98.5445	152.0859	209.8858	229.6060	10.1267
10	10.0000	98.4423	167.0175	209.8772	229.1549	10.4920
11	17.8863	98.4784	175.0000	210.0406	229.5110	10.9163
12	24.9744	124.9736	162.1321	209.9039	229.6327	11.6167
13	54.5440	98.6274	122.1321	209.7132	229.5059	10.5226
14	30.0000	80.0000	112.6484	248.1228	229.5478	10.3190
15	35.1027	80.0000	113.1176	209.9138	225.0000	9.1341
16	30.0000	98.3443	74.3805	209.6792	175.0000	7.4041
17	30.0000	68.3642	106.9694	209.3168	150.0000	6.6504
18	30.0000	98.3211	77.9997	209.7926	200.0000	8.1134
19	30.0000	90.0067	104.0650	209.7814	229.3679	9.2209
20	55.0000	106.8368	112.8146	210.2756	229.6649	10.5919
21	60.0000	90.4225	100.6334	209.4939	229.3635	9.9132
22	30.0002	98.4843	70.0000	209.6098	205.0002	8.0945
23	40.1292	98.4864	30.0000	209.8031	155.0002	6.4189
24	55.0000	80.0000	32.8253	160.0000	139.9531	4.7784
Cost=45590$, Emission=23567$lb$, Loss=194.8786$MW$						

Table 1: Hourly power schedule obtained from DEED ($\omega = 1$).

6- CONCLUSIONS

This paper propose a hybrid DE-SQP technique for solving the DEED with valve-point effects and prohibited operating zones. DE is first applied to find the best solution. This best solution is given to SQP as an initial condition fine-tune the optimal solution at the final. The feasibility and efficiency of the DE-SQP were illustrated by conducting case study with system consisting of five units.

H	P_1	P_2	P_3	P_4	P_5	*Loss*
1	30.0000	91.2604	112.5895	40.0000	139.7508	3.6007
2	48.1619	98.4595	112.6482	40.0000	139.7781	4.0477
3	60.0000	92.2948	112.7559	74.8542	139.8010	4.7060
4	55.0000	98.6121	117.4589	124.8542	139.9033	5.8285
5	69.4989	80.0000	140.0000	124.8950	150.0000	6.3938
6	75.0000	98.6695	117.0437	125.0404	200.0000	7.7535
7	55.0000	80.0000	144.8943	124.8805	229.4121	8.1870
8	75.0000	80.0000	153.5515	124.9189	229.4478	8.9183
9	74.9666	98.3931	140.0000	159.8534	226.7421	9.9552
10	75.0000	80.0000	120.1117	209.8534	229.5198	10.4850
11	75.0000	98.7383	118.0206	209.7653	229.4800	11.0041
12	74.6451	98.4222	140.0000	209.7362	228.7077	11.5113
13	74.9720	98.4564	112.7134	209.7431	218.6471	10.5321
14	64.5203	98.4539	112.7523	209.7247	214.6697	10.1208
15	60.0000	98.5006	112.6271	191.9150	200.0000	9.0426
16	75.0000	80.0000	121.9653	160.0000	150.0000	6.9653
17	75.0000	80.0000	112.7477	156.8903	139.8242	6.4622
18	60.0000	96.8322	112.6908	206.5352	139.7868	7.8450
19	55.0000	105.5763	152.6908	209.8543	139.8612	8.9826
20	55.0000	99.4524	175.0000	209.8580	175.0000	10.3105
21	55.0000	125.0000	152.7381	210.0460	146.9799	9.7640
22	60.0000	95.0340	112.7381	205.3626	139.6253	7.7600
23	30.0000	90.0281	112.5355	200.4257	100.0000	5.9893
24	30.0000	98.5297	79.6788	209.7494	50.0000	4.9579
Cost=46625$, Emission=20527*lb*, Loss=191.1233*MW*						

Table 2: Hourly power schedule obtained from DEED ($\omega = 0.5$).

H	P_1	P_2	P_3	P_4	P_5	*Loss*
1	54.6733	58.2374	116.5708	110.6084	73.3581	3.4480
2	25.0000	65.4717	125.0000	123.4277	100.0000	3.8994
3	55.0000	69.3744	125.0000	130.2555	100.0000	4.6299
4	55.0000	80.0000	145.7027	151.7306	103.3661	5.7994
5	75.0000	80.0000	125.0000	160.0000	124.4428	6.4428
6	75.0000	80.0000	160.6116	180.0000	120.0315	7.6431
7	75.0000	80.0000	167.6383	183.1452	128.3092	8.0927
8	55.0000	103.1532	169.2726	185.4532	150.0000	8.8790
9	75.0000	90.0000	154.8648	180.0000	200.0000	9.8648
10	75.0000	96.7608	162.5055	180.0000	200.0000	10.2663
11	75.0000	102.5241	168.6666	184.5539	200.0000	10.7446
12	75.0000	112.3949	165.0000	199.0108	200.0000	11.4057
13	75.0000	113.6897	125.0000	200.7737	200.0000	10.4634
14	55.0000	99.6718	165.0000	180.2054	200.0000	9.8773
15	55.0000	91.3382	156.5156	160.0000	200.0000	8.8537
6	55.0000	96.9966	125.0000	160.0000	150.0000	6.9966
17	55.0000	99.2419	125.0000	160.0000	125.2470	6.4889
18	55.0000	107.7033	125.0000	192.1129	135.9805	7.7967
19	55.0000	104.8769	165.0000	188.0166	150.0000	8.8934
20	55.0000	103.5150	169.7195	186.0565	200.0000	10.2909
21	25.0000	107.6038	165.0000	192.1003	200.0000	9.7041
22	55.0000	100.8150	125.0000	181.8512	150.0000	7.6662
23	25.0000	97.0241	125.0000	160.0000	125.8146	5.8387
24	55.0000	67.0241	124.1628	121.2012	100.0000	4.3881
Cost=52611$, Emission=18955*lb*, Loss=188.3739*MW*						

Table 3: Hourly power schedule obtained from DEED ($\omega = 0$).

state	*w* = 1		*w* = 0.5		*w* = 0	
Method	C ($)	E (*lb*)	C ($)	E (*lb*)	C ($)	E (*lb*)
SA[24]	47356	–	–	–	–	–
APSO[25]	44678	–	–	–	–	–
AIS[26]	44385.43	–	–	–	–	–
GA[27]	44862.42	–	–	–	–	–
PSO[27]	44253.24	–	–	–	–	–
ABC[27]	44045.83	–	–	–	–	–
MSL[28]	49216.81	–	–	–	–	–
HS[29]	44376.23	–	–	–	–	–
DE[18]	45800	–	–	–	–	–
PS[23]	46530	–	4791	18927	–	18192
EP[23]	46777	–	–	–	–	17966
PSO[22]	47852	22405	5089	20163	53086	19094
DE-SQP[6]	**43161**	**23080**	**4445**	**19616**	**51967**	**17853**

Table 4: Compassion results for 5 unit system.

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Appendix:

Gen	1	2	3	4	5
a_i	0.008	0.003	0.0012	0.001	0.0015
b_i	2	1.8	2.1	2	1.8
c_i	25	60	100	120	40
e_i	100	140	160	180	200
f_i	0.042	0.04	0.038	0.037	0.035
α_i	0.0180	0.0150	0.0105	0.0080	0.0120
β_i	-0.805	-0.555	-1.355	-0.600	-0.555
γ_i	80	50	60	45	30
η_i	0.6550	0.5773	0.4968	0.4860	0.5035
δ_i	0.02846	0.02446	0.02270	0.01948	0.02075
$P_i^{\min}$	10	20	30	40	50
$P_i^{\max}$	75	125	175	250	300
DR_i	30	30	40	50	50
UR_i	30	30	40	50	50
POZs-1	[25 30]	[45 50]	[60 70]	[95 110]	[80 100]
POZs-2	[55 60]	[80 90]	[125 140]	[160 180]	[175 200]

Table 5: Data of the five-unit system**.**

Time (h)	Demand (MW)	Time (h)	Demand (MW)
1	410	13	704
2	135	14	690
3	475	15	654
4	530	16	580
5	558	17	558
6	608	18	608
7	626	19	654
8	654	20	704
9	690	21	680
10	704	22	605
11	720	23	527
12	740	24	463

Table 6: Load demand of the five-unit system for 24 hours.

$$B_{ij} = 10^{-4} \times \begin{pmatrix} .49 & .14 & .15 & .15 & .20 \\ .14 & .45 & .16 & .20 & .18 \\ .15 & .16 & .39 & .10 & .12 \\ .15 & .20 & .10 & .40 & .14 \\ .20 & .18 & .12 & .14 & .35 \end{pmatrix} \text{per} MW$$

The transmission loss formula coefficients of five units.