Dynamic Economic Dispatch Based on Simple Algorithm

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Abstract—This paper presents a simplified methodology to solve Dynamic Economic Dispatch (DED) problems. The main objective is to determine the most economic dispatch of on line generating units with the predicted load demands over a certain period of time. The DED is formulated as a second order dynamic optimization problem that takes into the consideration of the ramp rate limits of the generating units. The simplified methodology optimizes or provides the most economic schedule of generation for each interval in the scheduling time horizon hence the minimization of the total fuel cost is achieved. The feasibility of the proposed methodology is demonstrated for solving the dynamic economic dispatch problem with suitable test systems. The unit operation constraint and transmission loss are considered for the practical applications. The simulation results are compared with the recent reports in terms of solution quality. Numerical simulation results indicate an improvement in total fuel cost saving and hence the superiority of the proposed is also revealed for dynamic economic dispatch problems.

Index Terms—Dynamic economic dispatch, ramp rate limits, sequential approach, transmission loss.

I. INTRODUCTION

The primary objective of the economic dispatch problem is to schedule the generations of the online thermal units so as to meet the required load demand at minimum operating cost while satisfying the unit and system equality and inequality constraints. Dynamic Economic Dispatch (DED) is an extension of the economic dispatch problem and it aims to schedule the online thermal units with the predicted load demands over a scheduling period at minimum operating cost. DED problem is formulated as minimization of total fuel cost is the main objective while satisfying system constraints. The fuel cost of the thermal plant is normally expressed as a quadratic function of real power output of generating units hence DED problem has been formulated as a second order quadratic optimization problem that takes into the consideration of the ramp rate limits of the generating units [1-2].

In general, the DED problem has been solved by splitting the entire scheduling period in to small intervals. The economic schedule of thermal units for each interval is determined subject to power balance constraint of the interval

and unit operational constraints. The static or traditional economic dispatch has been performed in each interval of the scheduling period. A variety of optimization techniques have been used for solving static or traditional economic dispatch problems. The conventional methods include the lambda-iteration method, the base point and participation factors method, the gradient method, the Lagrangian relaxation method and dynamic programming. The methods based on artificial neural network and heuristic search techniques based solution methodologies have been applied to solve economic dispatch problems.

The methods based on artificial intelligent techniques, such as Simulated Annealing (SA), Genetic Algorithm (GA), Evolutionary Programming (EP) and Particle Swarm Optimization (PSO) have been given attention for solving dynamic economic dispatch problem because of their ability to find the solution near global optimal. Simulated Annealing is the stochastic optimization technique has been applied to find the solution of economic and dynamic economic dispatch problems [3]. The SA technique is similar to local search technique in optimization, which can guarantee only a local optimum. The appropriate setting of control parameters is also important for convergence and improper setting of control parameters may lead execution time. Artificial neural network based solution for economic dispatch problem has been reported [4]. The heuristic search technique, Genetic algorithm has been successfully applied to find the economic schedule of generation for economic dispatch problems [5- 7]. Evolutionary Programming technique is search algorithm based on the simulated evolutionary process of selection, variation and genetics. Evolutionary programming is more flexible and robust than conventional calculus method. Evolutionary programming technique and its modified versions have been successfully applied for solving economic dispatch problems [8]. Particle Swarm Optimization (PSO) is a modern heuristic search technique, has been developed through simulation of a simplified social system. PSO algorithm has been successfully applied to find the solution for traditional and dynamic economic dispatch problems [9].

The traditional or classical approaches and the methods based on operational research artificial intelligent concepts have been applied for solving the Dynamic Economic Dispatch problem. The classical methods such as Lagrangian Relaxation, Dynamic programming approach is accurate but suffers for non linear search spaces and large scale systems. A various artificial intelligence based methods have been developed in order to attain an improvement in the solution quality. The price based ramp model has been used to solve

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the dynamic economic dispatch problem [10]. The solution methodology using Hopfield network model has been suggested for solving dynamic economic dispatch problem [11-13]. Particle Swarm Optimization method has been successfully applied to solve DED problem [14]. The hybrid approaches have been developed to solve dynamic economic dispatch problem. A hybrid approach has been developed by combining Hopfield Neural Network and Quadratic Programming (HNNQP), has been applied for the solution of DED problems [15-16]. The authors suggested Hopfield Neural Network and quadratic programming for solving static or traditional economic dispatch part and dynamic part respectively. The DED problem has been solved by Brent Method (BM) and it is applied to determine the optimal lambda [17]. The solution techniques based on SA and hybrid EP-PSO-Sequential Quadratic Programming (SQP) have also been reported [18-19]. A survey of literature on the DED solution methods reveals that various numerical optimization techniques have been employed to approach the DED problem [20]. It is observed that the traditional and heuristic methods have some limitations to solve DED problems. The traditional methods suffer with large execution time and the heuristic methods are unable to find the optimal solution within the reasonable execution time due to their heuristic nature.

In this article, a direct search methodology based on Sequential Approach with Matrix Framework (SAMF) has been applied to solve dynamic economic dispatch problems. The proposed methodology has been validated with three test systems.

II. PROBLEM FORMULATION

The DED problem is formulated as the minimization of total fuel cost of generating units for the entire scheduling period subject to variety of constraints. The DED problem formulation is as follows.

A. Objective function

The main objective of DED problem is to minimize the generation cost of 'n' online thermal units over a scheduling period 'T' is given as,

$$\min F = \sum_{t=1}^T \sum_{i=1}^n FC_{i,t}(P_{i,t}) \quad (1)$$

Where, $FC_{i,t}$ is the fuel cost of unit i at time interval t in \$/h and $P_{i,t}$ is the real power output of generating unit i at time period t in MW.

The fuel cost (FC) of generating unit at any time interval 't' is normally expressed as a quadratic function is as,

$$FC = \sum_{t=1}^T \sum_{i=1}^n a_i P_{i,t}^2 + b_i P_{i,t} + c_{i,t} \quad (2)$$

Where, a_i , b_i and c_i are the cost coefficients of generating unit i .

B. Constraints

The objective function is minimized subject to variety of constraints.

1) Power balance constraint

This constraint is based on the principle of equilibrium that

the total generation at any time interval 't' should satisfy the load demand at the interval 't' and transmission loss. This constraint is mathematically expressed as,

$$\sum_{i=1}^n P_{i,t} = P_{D,t} + P_{L,t} \quad (3)$$

Where, $P_{D,t}$ and $P_{L,t}$ are the load demand and transmission loss in MW at time interval 't' respectively.

The transmission loss can be expressed using through B coefficients.

$$P_{L,t} = \sum_{i=1}^n \sum_{j=1}^n P_{i,t} B_{ij} P_{j,t} + \sum_{i=1}^n B_{0i} P_{i,t} + B_{00} \quad (4)$$

Where, B_{ij} , B_{0i} and B_{00} are the loss coefficients.

2) Generator operational constraints

The generating unit operational constraints such as minimum/maximum generation limit, ramp rate limits and prohibited operating zones are as follows.

a) Generator capacity constraint

$$P_{i,min} \leq P_i \leq P_{i,max} \quad (5)$$

Where, $P_{i,min}$ and $P_{i,max}$ are the minimum and maximum real power generation of unit i in MW.

b) Ramp rate limits

The inequality constraints due to ramp rate limits for unit generation changes are given

1) as generation increases

$$P_i - P_i^0 \leq UR_i \quad (6)$$

2) as generation decreases

$$P_i - P_i^0 \leq DR_i \quad (7)$$

The generator operation constraint after including ramp rate limit of generators can be described as,

$$\max(P_{i,min}, P_i^0 - DR_i) \leq P_i \leq \min(P_{i,max}, P_i^0 + UR_i) \quad (8)$$

where, P_i^0 , DR_i and UR_i are the real power output of generator i before dispatched hour in MW, down ramp and up ramp limit of generator i in MW/h respectively.

III. SOLUTION METHODOLOGY

A. Economic dispatch solution using SAMF

Sequential approach with matrix framework has been developed for solving economic dispatch problems. A maiden attempt has been made to determine the optimal generation dispatches of a system for all possible load demands in single execution. The demonstration of the solution methodology is presented in this section.

The electric power production in a power plant is allowed to vary from minimum technical limit (P_{min}) to maximum technical limit (P_{max}). Initially the $P_{i,min}$ of all generating units in a power plant are considered as initial state input values and is represented by a single dimensional matrix as,

$$S = [P_{1,min} \ P_{2,min} \ P_{3,min} \ \dots \ P_{n,min}] \quad (9)$$

Based on the above single dimensional matrix, a square matrix (I) is developed to identify the economic schedule of generation. The formation of the square matrix is as follows. The process starts with a step increment in generation by Δ MW in $P_{1,min}$ by keeping the remaining units at its input value.

This will form first row of the square matrix.

$$I_l = [P_{l,min} + \Delta P_{2,min} P_{3,min}, \dots, P_{n,min}] \quad (10)$$

The increment in generation is made in the second element by keeping the other elements at its input value that leads to the development of second row of the square matrix.

$$I_2 = [P_{1,min} \ P_{2,min} + \Delta \ P_{3,min}, \dots, P_{n,min}] \quad (11)$$

In the same logic, an increment is made for remaining units one at a time and a square matrix with a dimension equal to the number of units has been developed. For every step increment in the operating range of the plant the unit one at a time is allowed to experience the change in generation thus leads to the formation of the square matrix.

$$I = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} P_{l,min} + \Delta & P_{2,min} & \dots & P_{n,min} \\ P_{l,min} & P_{2,min} + \Delta & \dots & P_{n,min} \\ \vdots & \vdots & \ddots & \vdots \\ P_{l,min} & P_{2,min} & \dots & P_{n,min} + \Delta \end{bmatrix} \quad (12)$$

Each element in the square matrix represents the generation of a unit corresponding to the column that should satisfy the unit capacity constraints.

In the square matrix the unit generations of each row that satisfy the constraints are identified and total fuel cost of generation is evaluated. The desired economic schedule of generation is identified by analyzing fitness of each row. The fitness function of each row is calculated as,

$$fit(j) = \frac{F_T(j)}{(pd + \Delta)} \quad j = 1, 2, \dots, n \quad (13)$$

where, pd is the total of input values.

The schedule with the minimum fitness is chosen as the successive state input values. This process is repeated till all the generating units reach their maximum generation capacity. The feasible solutions for every increment from $P_{\min}$ to $P_{\max}$ are obtained and hence the best solution for any load demand falls in the operating boundary can be easily sited.

The detailed computational flow of SAMF is presented in Fig. 1. The proposed methodology in the form of matrix framework to support the demonstration is as follows.

IV. IMPLEMENTATION OF THE PROPOSED METHOD

The solution methodology for solving dynamic economic dispatch problem is presented in this section. The scheduling period is divided into a number of intervals. The optimal dispatches of online thermal units are determined for each interval hence the minimum total fuel cost for entire

scheduling period is achieved.

Consider a thermal plant consist of 'n' thermal plants with a scheduling period of 'T'. The entire scheduling period is divided into a number of small intervals and the load demand for each time interval is predefined. For the first interval in the scheduling period, the unit operational constraints are also enforced and SAMF is performed to obtain the optimal dispatch of generating units.

Fig. 1. Computational flow of SAMF

For second interval in the scheduling period, the real power output of the previous interval determines the minimum and maximum operating region of the generating units and considering these limits again the SAMF is performed to obtain the optimal dispatch of generating units. This process is repeated till the optimal dispatches obtained for all intervals. The computational flow of the proposed methodology is presented in Fig. 2. The algorithmic steps of the proposed methodology are as follows.

Step 1: Read system data including unit characteristics, scheduling period (T) and load demand for each interval.

Step 2: Set interval = 1;

Step 3: Calculate the minimum operating limit of each generating unit after enforcing the ramp rate limits.

Step 4: Perform SAMF and obtain the optimal dispatch of generating units.

Step 5: Check if interval == T, goto Step 7 else goto next Step.

Step 6: Set interval = interval + 1 and update the minimum and maximum operating limit of each generating unit.
Step 7: Calculate the total fuel cost for the entire scheduling period.
Step 8: Print the results.
Step 9: Stop.

Fig. 2. Solution methodology for solving DED problem

V. SIMULATION RESULTS AND DISCUSSIONS

The proposed methodology for solving DED problem is implemented in Matlab 7.0 platform and executed with Pentium IV, 2.8 GHz personal computer. The effectiveness of the proposed methodology has been tested with three different scale of power system cases. The six unit, ten unit and fifteen unit system are considered for the analysis. The generating unit operational constraint, ramp rate limits and transmission loss are considered. The optimal dispatch of generators for each interval is obtained by SAMF. In SAMF, the selection of increment is important, too large increment may end up with unfeasible solution and too small increment may take long execution time. Based on experience, the desired increment is chosen as 1 MW.

A. Case 1: 10 unit system

The cost coefficients, maximum and minimum generation limits, ramp rate limits and load demand for each interval are presented in the literature [15]. The scheduling period of 12 intervals is considered. The minimum and maximum load demands of the scheduling period are 5540 MW and 6041 MW. The optimal dispatches of units for each interval are obtained and the schedule of generation is presented in Table I. The solution obtained by SAMF is compared with

the recent report HHNNQP and the comparison is presented in Table II. The comparison clearly indicates that the proposed methodology provides a superior schedule.

TABLE I: THE OPTIMAL DISPATCHES OF TEN UNIT SYSTEM

U \ t	1	2	3	4	5	6
1	239	244	262	238	258	278
2	355	361	381	356	376	396
3	411	417	439	411	461	474
4	475	482	505	475	525	543
5	416	421	442	416	466	476
6	547	556	589	547	597	641
7	620	620	620	620	620	620
8	643	643	643	643	643	643
9	908	919	920	908	920	920
10	946	957	999	946	1 046	1 050
P _D	5560	5620	5800	5560	5990	6041
FC	173395	176058	184199	173395	189424	195494

U \ t	7	8	9	10	11	12
1	282	261	249	237	251	257
2	404	380	367	353	369	376
3	463	438	425	410	426	433
4	532	504	490	473	491	499
5	466	441	428	414	429	436
6	625	586	567	544	568	579
7	620	620	620	620	620	620
8	643	643	643	643	643	643
9	920	920	920	904	920	920
10	1046	997	971	942	973	987
P _D	6001	5790	5680	5540	5690	5750
FC	193579	183741	178745	172513	179195	181913

TABLE II: TOTAL COST COMPARISON OF CASE 1

Method	Total cost (\$)
HHNNQP [15]	2196210
SAMF	2181651

B. Case 2: Six unit system

The system contains six thermal units and the details including cost coefficients, generation limits, ramp rate limits, transmission loss coefficients and forecasted load demand of each interval are presented in the literature [17]. The transmission loss is calculated using B coefficients. The one day scheduling period is divided into 24 intervals. The optimal dispatch of generating units is determined by SAMF. The minimum and maximum operating limit of each generating unit is obtained by enforcing the ramp down and ramp up limits of generating unit with the real power dispatch of previous interval. The minimum and maximum load demand in the scheduling period is 930 MW and 1263 MW respectively. The optimal dispatches of the entire scheduling period are presented in Table III. The solution obtained by SAMF method and Brent method are compared. The comparison is presented in Table IV. From the comparison, it is clear that the proposed methodology provides an improvement in the total cost savings.

C. Case 3: 15 unit system

The cost coefficients, maximum and minimum generation limits, load demand for each interval and the transmission loss coefficients are presented in the literature [17]. The transmission loss is calculated using transmission loss coefficients. The one day scheduling period is considered and the scheduling period is divided into 24 equal intervals. The minimum and maximum load demands of the scheduling

period are 2226 and 2970 Mw. The optimal dispatches of units for each interval are obtained and the schedule of generation is presented in Table V. The solution obtained by SAMF and BM are compared and the comparison is presented in Table VI. The comparison clearly indicates that the proposed methodology provides a better schedule than recent reports.

The total execution time of the different methods for the solution of DED problems are presented in Table VII. The execution times shown may not be directly comparable due to different configuration of computer hardware and programming languages used but some insight can be gained.

This comparison indicates that the proposed takes less execution time than other heuristic search methods.

The proposed methodology has following merits.

- From these studies, this approach has the competence to solve dynamic economic dispatch problem.
- In all cases, the proposed methodology provides the best schedule of generation with minimum total fuel cost hence the global optimal solution.
- The performance of the proposed approach is independent of the number of generating units in the system and hence it is suitable for system of any size.
- The computational procedure is minimal.

TABLE III: THE OPTIMAL DISPATCHES OF SIX UNIT SYSTEM

t \ U	1	2	3	4	5	6	P _D	P _L	Fuel Cost (\$)
P _i ⁰	340	134	240	90	110	52	---	---	---
1	380.3484	124	211	84	113	50	955	7.3484	11420.26
2	377	121	209.1497	82	110	50	942	7.1497	11257.52
3	375	120	208.0632	80	109	50	935	7.0632	11170.22
4	374	119	206.9952	79	108	50	930	6.9952	11107.97
5	375	120	208.0632	80	109	50	935	7.0632	11170.22
6	382	125	213.4453	86	114	50	963	7.4453	11520.50
7	389	130	217.8196	91	119	50	989	7.8196	11848.34
8	397	136	224.3228	98	126	50	1023	8.3228	12280.80
9	419	152	241.8625	116	143	64	1126	9.8625	13614.64
10	424	156	245.2431	120	147	68	1150	10.2431	13930.14
11	434	164	254.0921	128	155	77	1201	11.0921	14606.48
12	441	169	256.6832	134	161	82	1235	11.6832	15061.82
13	432	162	251.9155	126	154	75	1190	10.9155	14459.92
14	445	171	261.9562	137	163	85	1251	11.9562	15277.34
15	447	173	264.1730	139	165	87	1263	12.1730	15439.50
16	445	171	261.9535	136	163	85	1250	11.9535	15263.85
17	439	167	257.4419	131	158	80	1221	11.4419	14873.90
18	435	164	254.1117	128	155	77	1202	11.1117	14619.82
19	426	157	247.3925	121	148	70	1159	10.3925	14048.91
20	412	147	236.3508	110	138	58	1092	9.3508	13170.71
21	397	136	224.3228	98	126	50	1023	8.3228	12280.80
22	388	129	216.747	90	118	50	984	7.7470	11785.10
23	385	127	215.6239	88	117	50	975	7.6239	11671.50
24	381	125	212.4087	85	114	50	960	7.4087	11482.84
Total cost (\$)									313363.12

TABLE IV: TOTAL COST COMPARISON OF CASE 2

Method	Total cost (\$)
λ - iteration [17]	313 405.65
BM [17]	313 405.40
SAMF	313 363.12

TABLE V: THE OPTIMAL DISPATCHES OF FIFTEEN UNIT SYSTEM

t \ U	1	2	3	4	5	6	7	8	9	10	11	12
1	299.4497	379	379	380	398	404	411	452	455	455	455	455
2	330	356.3711	295.4111	297.4924	323.4391	333.7384	344.0506	406.1324	455	455	455	455
3	130	130	130	130	130	130	130	130	130	130	130	130
4	130	130	130	130	130	130	130	130	130	130	130	130
5	306	186	150	150	150	150	150	150	229.7866	309.0364	353.307	356.4864
6	283	363	443	445	460	460	460	4604	460	460	460	460
7	367	447	465	465	465	465	465	465	465	465	465	465
8	163	63	60	60	60	60	60	60	60	60	60	60
9	25	25	25	25	25	25	25	25	25	25	25	25
10	34	25	25	25	25	25	25	25	31	51	63	64
11	56	40	34	34	37	38	38	44	77	80	80	80
12	80	55	51	51	53	54	54	59	80	80	80	80
13	27	30	27	32	31	31	29	29	28	27	27	26
14	16	15	15	15	15	15	15	15	15	15	16	15
15	15	15	15	15	15	15	15	15	15	15	15	15
P _D	2236	2240	2226	2236	2298	2316	2331	2443	2630	2728	2783	2785
P _L	25.4497	19.3711	18.4111	18.4924	19.4391	19.7384	20.0506	22.1324	25.7866	29.0364	31.3070	31.4864
Fuel cost (\$)	28597.94	28428.80	28254.82	28372.95	29021.31	29210.60	29363.23	30545.24	32544.89	33612.99	34221.62	34240.72
t \ U	13	14	15	16	17	18	19	20	21	22	23	24

1	455	455	455	455	455	455	455	455	449	405	387	385
2	455	455	455	455	455	455	454.9164	155	400.9532	333.7478	307.893	303.7556
3	130	130	130	130	130	130	130	130	130	130	130	130
4	130	130	130	130	130	130	130	130	130	130	130	130
5	352.2556	387.3713	447	469.6199	437.7371	363.9267	252	207.8932	150	150	150	150
6	460	460	460	460	460	460	460	460	460	460	454	451
7	465	465	465	465	465	465	465	465	465	465	465	465
8	60	60	100.5715	60	60	60	60	60	60	60	60	60
9	25	25	25	25	25	25	25	25	25	25	25	25
10	63	76	111	118	93	67	34	25	25	25	25	25
11	80	80	80	80	80	80	77	64	44	38	35	35
12	80	80	80	80	80	80	80	75	58	54	52	52
13	26	28	29	28	29	27	25	27	27	26	29	31
14	15	17	27	19	24	22	15	15	15	15	15	15
15	15	15	15	15	15	15	15	15	15	15	15	15
P _D	2780	2830	2970	2950	2902	2803	2651	2584	2432	2312	2261	2254
P _L	31.2556	33.3713	40.7215	39.6199	36.7371	31.9267	26.9164	24.8932	21.9532	19.7478	18.893	18.7556
Fuel cost (\$)	34185.25	34747.62	36363.14	36100.99	35563.14	34450.09	32770.22	32044.57	30423.76	29155.44	28627.38	28559.18
Total cost (\$) = 759406.42												

TABLE VI: TOTAL COST COMPARISON OF CASE 3

Method	Total cost (\$)
BM [17]	760287.232
SAMF	759406.42

TABLE VII: TOTAL EXECUTION TIME

Test system	Execution time (s)
6 unit system	1.965
10 unit system	0.624
15 unit system	2.951

VI. CONCLUSION

This article presents a simple and efficient direct search approach based on sequential approach with matrix framework for solving dynamic economic dispatch problems. The effectiveness of the proposed methodology is validated by solving the different scale of dynamic economic dispatch problems. The practical operational constraint of generators like ramp rate limits and transmission loss are included in the analysis. The proposed SAMF provides the most economical dispatches for each interval in the scheduling period hence the optimal solution for DED problem. The simulation results of different case studies are compared with the earlier reports. The comparison of results concludes that the proposed methodology provides the minimum total fuel cost hence global optimal solution for dynamic economic dispatch problems.

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