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Optimal Scheduling for Dynamic Loads Using Direct Method

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Abstract

The main objective of the dynamic economic dispatch problem is to determine the optimal schedule of output powers of all generating units to meet the load demands and losses at minimum operating cost while satisfying ramp rate and power limits. In addition, the computing time should be as soon as possible because of the scheduling interval in an hour. This paper proposed an application of the direct method with cost functions of the generator units in the quadratic form to solve the problem. In which the proposed method is simplest, applicable and having shortest computing time. To validate the proposed method was done evaluating for 6-generator units in detail and the results compared to the other methods. While to test computing time was done a simulation to the large power system, 47 generator units of Jawa-Bali System. The results state that the proposed method can work efficiently and accurately. These are in line with expectations.

Keywords: accurately, economic dispatch, efficiently, quadratic objective function, ramp rate limits.

1. Introduction

Scheduling of generating units, units, to meet system loads and losses must involve ramp rate limits of each unit because of the unit is not free to raise/down its power. Involving of the ramp rate will guarantee the optimal results for scheduling can be implemented to meet dynamic system loads and losses. A few methods have published in solving an economic dispatch problem, EDP, namely:

- Conventional methods have been published such as iteration lambda method, gradient method, Newton method, linear method and dynamic programming method (A .J. Wood, et al., 1984; Salama, M., M., 1999 and IEEE Committee Report, 1971). These methods work by iteration process so that can take enough large computational time because it must be through iteration process steps. The addition of the computational time will be seen significantly if the economic dispatch problem with large scale. Sometimes these methods cannot converge in the process of iteration.
- Methods based on the artificial intelligent concept such as artificial neural network (J. Nanda, et al. 1997), particle swarm optimization, PSO, (Z. L. Gaing, 2004; J. B. Park, et al., 2005 and D. N. Jeyakumar, et al., 2006) and genetic algorithm, GA, (D. C. Walters, et al., 199; J. Tippayachai, et al. 2003.). The main problem associated with these methods is the need for appropriate control parameters. Sometimes the methods take large computational time due to improper selection of the control parameters.

The methods that were mentioned above are always the completions through iteration process so it can take large computation time. This paper will propose a method without iteration, i.e. the direct method that has been studied by (H. Zein, et al., 2012), so that is expected to reduce the computation time and simpler so easy to be applied. So, this method will be more effective for a dynamic economic dispatch with large scale. But it is limited by cost function of each generator unit in the quadratic form. The formulations have been derived with very clear. Then, the proposed method is verified with doing a test for a system that consists of 6 units through a numerical study. In this study to see the optimal results of the proposed method whether they violate of the ramp rate limit constraints or not. In addition, through this numerical study was conducted also verified the calculation results to the results of the other methods.

2. Research method

2.1. Formulation of a dynamic economic dispatch

The primary objective of an EDP is to minimize the total fuel cost of power plants subjected to the operating constraints of a power system. In general, the EDP can be formulated mathematically as a constrained optimization problem with an objective function of the form:

$$F_T = \sum_{i=1}^{n} F_i(P_i) \tag{1}$$

Where *FT* is the total fuel cost of the system ($/hr), n is the total number of units and *Fi* (*Pi*) is the operating fuel cost of generator unit i ($/hr). Generally, the fuel cost function of the unit is expressed as a quadratic function as given in (2).

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \tag{2}$$

Where *Pi* is the real output power of unit i (MW), *ai* , *bi* and *ci* are the cost coefficients of unit i. The minimization of the EDP problem is subjected to the following constraints:

1. Real Power Balance Constraint: For power balance, an equality constraint should be satisfied. The total generated power should be equal to the total load demand plus the total line losses, system losses. The active power balance is given by:

$$\sum_{i=1}^{n} P_i = P_D + P_L \tag{3}$$

Where P_D is the total load demand (MW), P_L is the system losses (MW). The P_L value will be calculated through (15)

2. Generator Power Limit Constraint: The generation output power of each unit should lie between the minimum and maximum limits. The inequality constraint for each generator can be expressed as:

$$P_{i,\min} \le P_i \le P_{i,\max} \tag{4}$$

Where *Pi*,min and *Pi*,max are the minimum and maximum power outputs of generator i (MW), respectively. The maximum output power of the generator is limited by thermal consideration and minimum power generation is limited by the flame instability of a boiler.

3. Ramp Rate Limit Constraint: The generator constraints due to ramp rate limits of generating units, from [12], is given as:

- As Generation Increases:

$$P_i(t) - P_i(t-1) \le UR_i \tag{5}$$

- As Generation Decreases:

$$P_i(t-1) - P_i(t) \le DR_i \tag{6}$$

Therefore the generator power limit constraints can be modified as:

$$\max(P_{i,\min}, P_i(t-1) - DR_i) \le P_i(t) \le \min(P_{i,\max}, P_i(t-1) + UR_i) \tag{7}$$

From (7), the limits of minimum and maximum output powers of generating units are modified as:

$$P_{i,\min}(t) = \max(P_{i,\min}, P_i(t-1) - DR_i \tag{8}$$

$$P_{i,ma}(t) = \max(P_{i,\max}, P_i(t-1) + UR_i) \tag{9}$$

Where $Pi\ (t\ )$ is the output power of generating unit i (MW) in the time interval (t), $Pi\ (t\ -1)$ is the output power of generating unit i (MW) in the previous time interval (t-1), UR_i is the up ramp limit of generating unit i (MW/time-period) and DR_i is the down ramp limit of generating unit i (MW/time-period).

The ramp rate limits of the generating units with all possible cases are shown in Fig. 1.

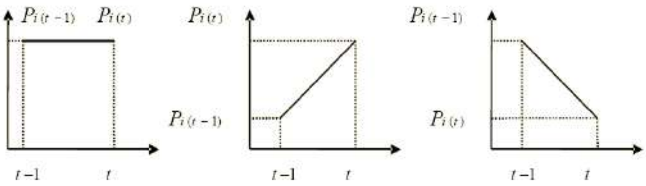

Fig. 1: Ramp rate limits of the generating units

2.2. Dynamic economic dispatch problem

A dynamic economic dispatch problem, DEDP, is to meet ramp rate limits, (5) and (6), in the power change of each unit from t-1 to t. So, the DEDP can be expressed by (10).

$$\text{Objective:} \quad F_T(t) = \sum_{i=1}^{n} F_i(P_i(t))$$

$$\text{Subject to:} \quad \sum_{i=1}^{n} P_i(t) = P_D(t) + P_L(t) \tag{10}$$

$$P_{i,\min}(t) \le P_i(t) \le P_{i,\max}(t)$$

In this paper is created the research for the objective function in quadratic form and estimated losses, like the problem expressed in the (10). This problem will be solved in two stages. Stage I does optimization without the power limits of units. Stage II evaluates the optimal results of stage I against violent of the power limits for each unit.

For the quadratic objective function (10) and assume P_L(t) constant, then LaGrange multiplier (lambda) at time t is:

$$\lambda(t) = b_i + 2c_i P_i(t) \tag{11}$$

Or,

$$P_i(t) = \frac{\lambda(t) - b_i}{2c_i} \tag{12}$$

Where Pi(t) is optimal power for unit-i at time t, $\lambda(\tau)$ is LaGrange multiplier at time t, c_i is price linear parameter for unit-i ($/MWH), bi is price quadratic parameter for unit-i ($/MWH2).

So for n-unit generators are:

$$\sum_{i=1}^{n} P_i(t) = \sum_{i=1}^{n} \frac{\lambda(t) - b_i}{2c_i} \tag{13}$$

From the last equation, the value of lambda can be obtained directly as expressed by (14) below.

$$\lambda(t) = \frac{P_D(t) + P_L(t) + \sum_{i=1}^{n} \frac{b_i}{2c_i}}{\sum_{i=1}^{n} \frac{1}{2c_i}} \tag{14}$$

While system losses at time t, $P_L(t)$, in the study are estimated with (15) below.

$$P_L(t) = P_L(t-1)\left(1 + f_c \frac{P_D(t) - P_D(t-1)}{P_D(t)}\right) \tag{15}$$

Where correction factor, f_c, is dependent on system conditions, like network structure, and load or power plant distributions, which the f_c value lies between 1 and 2.

Equation (14) shows the optimization of completion directly or without through iteration process, so the convergence is always guaranteed. Here needs to be noted that the (14) is valid only for the DEDP with the quadratic objective function. After lambda value has been determined by the (14) and continued to determine optimal power unit with the (12). Then, to be done evaluation against the minimum and maximum power limits to obtain optimal solution, $P_{i,o}(t)$, with the following terms.

If $P_{i,o}(t) < P_{i,min}(t)$, then $P_{i,o}(t) = P_{i,min}(t)$ (16)

If $P_{i,o}(t) > P_{i,max}(t)$, then $P_{i,o}(t) = P_{i,max}(t)$ (17)

2.3 Algorithm of the Proposed Method

The following is the steps of completion algorithm for DEDP with the proposed method and it has been described above.

1. Input data
2. Calculate $P_L(t)$ through (15).
3. Remove the unit is not changed and update load by the (18).
4. Update generating power limits through the (8) and (9).
5. Calculate λ through (14)
6. Calculate $P_i(t)$ through (12).
7. If $P_i(t)>P_{i,max}(t)$, then $P_{i,o}(t)=P_{i,max}(t)$, update $P_D(t)=P_D(t)-P_{i,o}(t)$, remove unit i and continue step 4.
8. If $P_i(t)<P_{i,min}(t)$, then $P_{i,o}(t)=P_{i,min}(t)$, update $P_D(t)=P_D(t)-P_{i,o}(t)$, remove unit i and continue step 4.
9. Set $P_{i,o}(t)=P_i(t)$ for not violate the generating power limits.
10. Results.
11. Stop.

From three possibilities of ramp rate, Fig. 1, Fig. 1a is the unit that does not change the power from t-1 to t so that satisfies Pi,o(t-1)=Pi,o(t). Then, this unit is removed in the optimization process and followed with updating system loads

$$P_D(t) = P_D(t) - \sum_{i=1}^{m} P_{i,o}(t) \qquad (18)$$

Where m is a number of the generator units that do not experience power change.

3. Numerical study

To verify the effectiveness of the proposed method, a six-unit power generating plant was tested. The Algorithm of the method has been implemented in the program using FORTRAN and laptop Asus core i3. It is applied to 6 generator units with power constraint and ramp rate limits. The fuel cost data and ramp rate limits of the six units were given in Table 1. The load demand for 24 hours is given in Table 2.

Table 1: Fuel cost coefficients and ramp rate limits of six units

Unit	a_i	b_i	c_i	$P_{i,min}$	$P_{i,max}$	UR_i	UD_i
1	240	7	0.007	100	500	80	120
2	200	10	0.0095	50	200	50	90
3	220	8.5	0.009	80	300	65	100
4	200	11	0.009	50	150	50	90
5	220	10.5	0.008	50	200	50	90
6	190	12	0.0075	50	120	50	90

Table 2: Load demand for 24 hours of six Units

Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)	Hour	Load (MW)
1	955	7	989	13	1190	19	1159
2	942	8	1023	14	1251	20	1092
3	935	9	1126	15	1263	21	1023
4	930	10	1150	16	1250	22	984
5	935	11	1201	17	1221	23	975
6	965	12	1235	18	1202	24	960

Table 3: Output power, losses and total fuel cost for 24 hours of 6 units

6 Hour	P_1	P_2	P_3	P_4	P_5	P_6	Loss	Fuel Cost
1	382.4	123.9	214.1	75.2	115.9	50.0	6.53	11409.3
2	379.3	121.6	211.7	72.8	113.1	50.0	6.37	11247.0
3	377.6	120.3	210.3	71.4	111.6	50.0	6.28	11159.9
4	376.4	119.4	209.4	70.5	110.6	50.0	6.22	11097.7
5	377.6	120.3	210.3	71.4	111.6	50.0	6.28	11159.9
6	384.4	125.3	215.6	76.7	117.6	50.0	6.62	11509.4
7	390.7	130.0	220.5	81.6	123.1	50.0	6.95	11836.4
8	398.9	136.1	227.0	88.1	130.3	50.0	7.37	12267.7
9	421.6	152.7	244.5	105.7	150.1	60.1	8.71	13598.2
10	426.3	156.2	248.3	109.4	154.3	64.6	9.05	13913.0
11	436.5	163.7	256.1	117.3	163.2	74.0	9.77	14587.4
12	443.2	168.7	261.4	122.5	169.1	80.3	10.27	15041.3
13	434.3	162.1	254.4	115.5	161.2	72.0	9.59	14441.0
14	446.4	171.0	263.9	125.0	171.9	83.3	10.48	15255.8
15	448.8	172.8	265.7	126.8	173.9	85.5	10.66	15417.3
16	446.2	170.9	263.7	124.8	171.7	83.1	10.46	15242.3
17	440.4	166.6	259.2	120.3	166.6	77.7	10.02	14853.5
18	436.7	163.9	256.3	117.4	163.3	74.2	9.74	14600.2
19	428.1	157.6	249.6	110.7	155.8	66.2	9.12	14030.7
20	414.8	147.7	239.3	100.4	144.2	53.8	8.17	13154.1
21	398.9	136.0	226.9	88.0	130.3	50.0	7.24	12266.0
22	389.4	129.1	219.6	80.7	122.0	50.0	6.74	11771.6
23	387.3	127.4	217.9	79.0	120.1	50.0	6.63	11658.3
24	383.6	124.8	215.0	76.1	116.9	50.0	6.45	11470.1
Total							**195.72**	**312988.0**

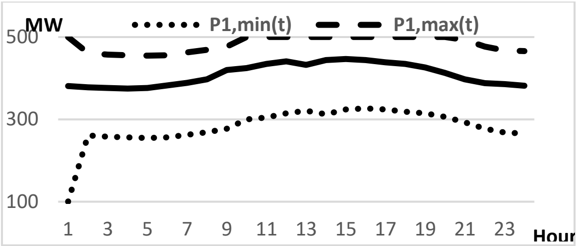

Fig. 2. Power limits and optimal power of unit 1 versus 24 hr

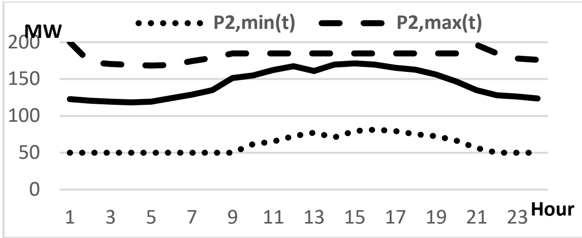

Fig.3. Power limits and optimal power of unit 2 versus 24 hr

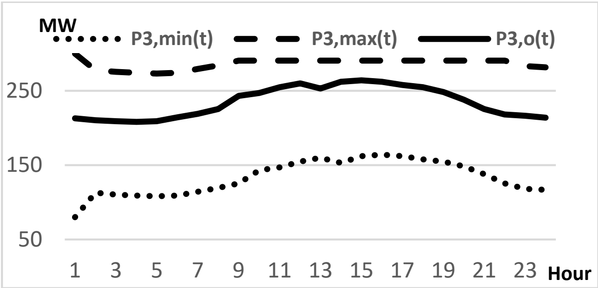

Fig. 4: Power limits and optimal power of unit 3 versus 24 hr

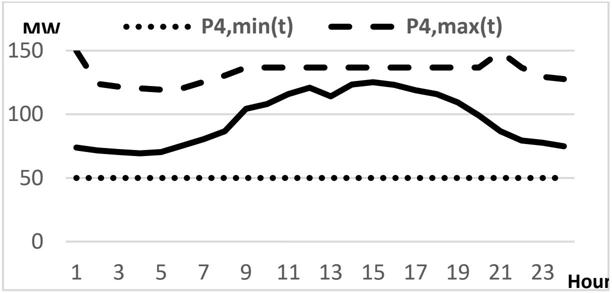

Fig. 5: Power limits and optimal power of unit 4 versus 24 hr

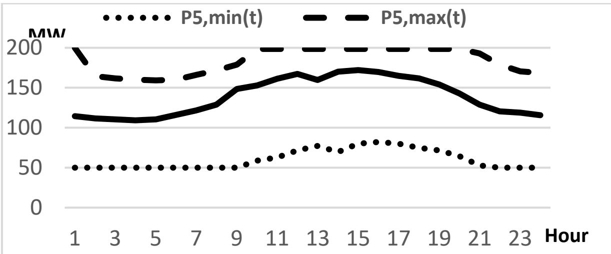

Fig. 6: Power limits and optimal power of unit 5 versus 24 hr

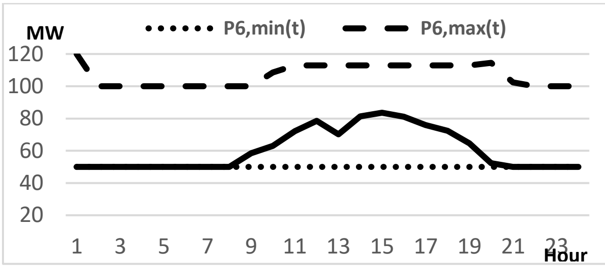

Fig. 7: Power limits and optimal power of unit 6 versus 24 hr

Table 4: Loss and total fuel cost comparison between 4 methods of 6 units

Method	Losses (MW)	Total Fuel Cost ($)
1. Lambda iteration method	-	313045.50
2. Particle Swarm Optimization (PSO)	193.49	313041.40
3. Genetic Algorithm (GA)	194.12	313040.90
4. Proposed Method	195.72	312988.00

While a simulation for the large power system, 47 generator units of Jawa-Bali System, was done successfully and satisfactory. For example, at peak load time,18 o'clock, with system load 13121 MW is obtained computating time of 0.98 seconds and losses of 215 MW. At minimum load time, 4 o'clock with system load 6038 MW is obtained computing time of 87 seconds and losses of 42 MW, The simulation results of 24 hours state that the proposed method can run the program in a very short time, i.e. computing time less than 1 second.

4. Discussion

- A method for calculating an economic dispatch in meeting load demand and losses with ramp rate and power limits has been proposed in this paper. This method is devoted to the dynamic economic dispatch problem with fuel cost function of generating unit in the quadratic form, (2). By using LaGrange optimization is obtained the direct solution of the lambda value, (14). Where the (14) will ensure that the optimization results fall at the point of minimum, but not necessarily optimal because it may violate the ramp rate constraints of generator units. Therefore, it is necessary to evaluate the results through (16) and (17).
- The solving steps of the DEDP have been stated in the algorithm above. The numerical study results for 6 units with system load changes in interval time 24 hours have met satisfy expectation. Optimal scheduling of

the generator units and fuel costs in the 24 hours are loaded in Table III. The results have met the ramp rate limits for every unit, shown in Fig. 2-7. Where the optimal results every hour, $P_{i,o}(t)$, do not violate the minimum and maximum dynamic power limits based on the ramp rate limits, Fig.1. it takes a very short time in the computing process in resolving the optimization problems.

- The contrast thing happened on unit 6, for interval time at 1-8 and 21-24, the optimal results are equal to minimum generating power limit. It is caused by the expensive fuel cost compared to the others so the optimal power less than the minimum generating power limit. Since each generator unit must be operated at least equal to the minimum power limit, then if the optimization results for each generator unit smaller than its minimum power limit will be set equal to the minimum power limit.
- Table IV is a comparison to the other methods, where the calculation results of all methods show the values almost same. From this table is seen that the proposed method produces the larger losses so that the total power generated is also greater than the other three methods. However, this method gives better results due to the total fuel costs are lower when is compared with three other methods.
- From simulation 47 generator of Jawa-Bali System with a minimum load, 6038 MW, at 4 o'clock and peak load, 13121 MW, at 18 o'clock, the proposed method could determine to schedule of the generator units successfully and satisfactory. The simulation results state that the proposed method can work in the short time, where it needs less than 1 second to execute the program. It is shortest compared to the interval time of scheduling, 1 hour.

5. Conclusion

A method for solving the dynamic economic dispatch problem has been proposed in this paper. This method is simpler and without iteration process like the published methods that mention above. It can reduce significantly the computational time. One other advantage is the assurance of completion will always converge. Thus, this proposed method is easy to be implemented and it is expected to work effectively for dynamic economic dispatch problem with large scale. Verification of the method with six generating units and simulation for 47 generator units of Jawa-Bali System has successfully done with satisfactory results. It only took about one second in the computing process of the 47 generator units of Jawa-Bali System. Where the results of the optimization of each unit do not violate the minimum and maximum dynamic constraint as shown in Fig. 2-7. From the comparison of the results with three other methods, Table IV, this method provides convincing results, where the calculation results are very close to the calculation results of three other methods. However, if observed in deeper this method gives better results due to the lower total fuel cost even though the larger system losses.

6. Nomenclature

kV	kilo volt	-
MW	mega Watt	-
n	number of unit	-
$	unit currency	-
hr.	hour	hour
t	time	hour

Greek letters

λ	LaGrange multiplier	$/MW

Subscripts

i	unit number
max	maximum
min	minimum

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