Effect of Including Emissions in Economic Dispatch

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Abstract: Economic load dispatch is an important optimization task in power system. It is the process of allocating generation among the committed units such that constraints imposed are satisfied. There are three criteria in solving the ELD problem: minimizing the total generation cost, scheduling of generating units and minimizing the total emission cost. Emissions have an effect on the fuel cost of the generating system. In this paper, the Lambda Iteration Method is used to solve the fuel cost equation and the emission equation, that have been combined into a Combined Emission and Economic Dispatch equation. The equations are combined using weighting factors. The effect of emissions on the fuel cost have been studied. The values of weighting factors have an effect on the respective values of fuel cost and emissions of the system. The weighting factors are varied to see the corresponding change in fuel cost and emissions. The results are compared and put in tabular form.

Keywords: Lambda Iteration, Economic dispatch, Emissions, Weighting factor, Combined Economic and Emission Dispatch, Multi- objective function.

1. Introduction

Successful Planning and operation of the power system is one of the most complex task of today's civilization.The basic requirement is to meet the demand of electrical energy of an area, at lowest possible cost. The size of electrical power system is increasing rapidly to meet the energy requirements. With the development of grid system; it becomes necessary to operate the plant unit most economically. The main aim of modern electrical power utility is to provide high quality and reliable power supply to the consumers at lowest possible cost and also operating in such a way so that it meets the constraints imposed on the generating units and considers environmental constraints. These constraints give rise to economic load dispatch (ELD) problem.

The problem of ED in power systems is to plan the power output for each devoted generator unit in such a way that the operating cost is minimized and simultaneously, matching load demand, power operating limits and maintaining stability. This problem becomes more complex in large scale power systems. Optimization of the power system plays a major role in thermal power plants energy production. The challenges for the engineers are to optimize the real power of the generators, to minimize the fuel cost and emission of the power plants. Thermal stations, during power production, burn fossil fuels that generate toxic gases in their effluent and these become a source of pollution for the environment. In fossil-fired power plants, main sources of energy are coal, gas, oil and diesel. All of the above mentioned resources realize harmful gases in atmosphere. Coal produces ash content, SO_x NO_x and CO_2 in the atmosphere. Emission control has become an important operational objective.

The cost minimum condition corresponds to minimum cost with considerable amount of emission combining both the objective functions into Combined Economic Emission Dispatch (CEED). The aim of CEED is to operate generators that produce energy in a power plant with optimized levels of fuel cost and emissions, while satisfying the load demand and operational constraints. In the solution of the CEED problem, the point at issue is to minimize fuel cost or emission, while satisfying equality and inequality

constraints. Cost and emission functions, which are independent of each other, make the CEED problem bi-objective. Bi-objective problem solving can be done by two objective functions turned into a single objective function.
Power system network optimization involves maximization or minimization of objective function under certain constraints. Since these two conditions cannot be implemented simultaneously, the bi-objective function, obtained by combining the fuel cost equation and the emissions equation using weighting factor combined into a single objective function is analysed to study the effect of emissions on the fuel cost of the generator set. The optimization of the multi objective function formed into single objective function is done using Lambda Iteration Method.

2. Economic Dispatch Problem

Reference [1] shows a system consisting of N thermal-generating units connected to a single bus-bar serving a received electrical load. The input to each unit is F_i. The output of each unit, P_i, is the electrical power generated by that particular unit. The total cost rate of this system is the sum of the costs of each of the individual units. The essential constraint on the operation of this system is that the sum of the output powers must equal the load demand.
Mathematically speaking, the problem may be stated very concisely. That is, an objective function, F_T, is equal to the total cost for supplying the indicated load. The problem is to minimize F_T subject to the constraint that the sum of the powers generated must equal the received load.
Note that any transmission losses are neglected and any operating limits are not explicitly stated when formulating this problem. That is,

$$F_T = F_1 + F_2 + \dots\dots\dots + F_N \tag{1}$$

$$F_T = \sum_{i=1}^{n} F_i(P_i) \tag{2}$$

$$\Phi = 0 = P_{LOAD} - \sum_{i=1}^{n} P_i \tag{3}$$

This is a constrained optimization problem may be solved using the Lagrange function. In order to establish the necessary conditions for an extreme value of the objective function, add the constraint function to the objective function after the constraint function has been multiplied by an undetermined multiplier. This is known as the Lagrange Function and is given by,

$$L = F_T + \lambda\phi \tag{4}$$

The necessary conditions for an extreme value of the objective function results when we take the first derivative of the Lagrange function with respect to each of the independent variables and set the derivatives equal to zero. In this case, there are $\boldsymbol{N} + 1$ variable, the $\boldsymbol{N}$ values of power output P_i plus the undetermined Lagrange multiplier λ. The $\boldsymbol{N}$ equations results when we take the partial derivative of the Lagrange function with respect to the power output values one at a time give the set of equations shown as Eq. 5

$$\frac{\partial L}{\partial Pi} = \frac{dFi(Pi)}{dPi} - \lambda = 0 \tag{5}$$

$$\frac{dFi}{dPi} - \lambda = 0 \tag{6}$$

Where, $\frac{dFi}{dPi}$ is the incremental cost rate for the unit '*i*'. That is, the necessary condition for the existence of a minimum cost operating condition for the thermal power system is that the incremental cost rates of all the units be equal to some undetermined value, $\boldsymbol{\lambda}$. Now to this necessary condition, we add the constraint that the sum of outputs must be equal to the power demanded.

2.1. Fuel Cost Function

The majority of generating systems are of three types- nuclear, hydro and fossil (coal, oil or gas). Nuclear plants tend to operate at constant output levels and hydro plants have essentially no variable operating cost. Therefore, the components of cost that fall under the category of dispatching procedures are the cost of fuel burnt in the fossils plants. The total cost of operation includes the fuel cost, cost of labour, supplies and maintenance. Generally cost of labour, supplies and maintenance are fixed percentages of incoming fuel costs. The economic load dispatch problem can be described as an optimization (minimization) process with the following objective function

$$Min\sum_{i=1}^{n} F_i(P_i) \tag{7}$$

Where, $F_i(P_i)$ is the total cost function of the ith unit, and P_i is the power generated by the ith unit.
The fuel cost function without valve-point loading of the generating unit is given by:

$$F_i\ (P_i) = a_iP_i^2 + b_i P_i + c_i \text{ ₹}/hr \tag{8}$$

Where, F_i is the fuel cost of ith unit, and a_i, b_i, c_i are the fuel cost coefficients of the i^{th} unit.

3. Emission Dispatch

Most electricity today is generated by burning fossil fuels and producing steam which is then used to drive a steam turbine that, in turn, drives an electrical generator. More serious are concerns about the emissions that result from fossil fuel burning. Depending on the particular fossil fuel and the method of burning, other emissions produced from burning fuel in a generating station are Ozone, Sulphur dioxide, NO_2 and other gases are often released, as well as particulate matter. Sulphur and nitrogen oxides contribute to smog and acid rain.These emissions also have an effect on fuel cost equation of a generating system.

3.1. Emission Function

The emission of the thermal power plant can be formulated as a second order polynomial function as

$$E_i = (a_iP_i^2 + \beta_iP_i + \gamma_i\ )\ \ kg/hr \tag{9}$$

Where, E_i is the Emission of an i^{th} unit, a_i ,β_i ,γ_i are the Emission coefficients of generating unit 'i'.

4. Constraints

There are two constraints that must be satisfied for each of the units. That is, the power output of each unit must be greater than or equal to the minimum power permitted and must also be less than or equal to the maximum power permitted on that particular unit.
Inequality Constraint is stated as:

$$P_{gimin} \leq P_{gi} \leq P_{gimax} \tag{10}$$

Where, P_{gimin} is the minimum power generation limit of i^{th} unit, and P_{gimax} is the maximum power generation limit of i^{th} unit.
Equality Constraint is stated as:

$$P_G = P_D + P_{LOSS} \tag{11}$$

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Where, P_G is the total generation,P_D is the total demand, and,$P_{LOSS}$is the loss in the system.

5. Multi-Objective Function

The fuel cost equation and the emission equation can be combined into a Combined Economic and Emission Dispatch Function using Weighting Factors.
Equation (8) can be written as

$$F_T = \sum_{i=1}^{n} F_i \tag{12}$$

Where, $i = 1, 2, 3$ for three generator system and $i = 1, 2, ..., 6$ for six generator system.
Equation (9) can be written as

$$E_T = \sum_{i=1}^{n} E_i \tag{13}$$

Where, $i = 1, 2, 3$ for three generator system and $i = 1, 2, \ldots, 6$ for six generator system.

5.1. Combined Economic and Emission Dispatch

Combining Equations 12 and 13 into a multi objective function as in [3] and [4]

$$C = W_1 (F_T) + W_2 (E_T) \tag{14}$$

Where, $W_1$and $W_2$are the weighting factors.
The power system combined economic and emission dispatch problem using Lambda Iteration method has been tested on 3 generator and 6 generator system. The flow chart of a simplified Lambda Iteration method is shown below:

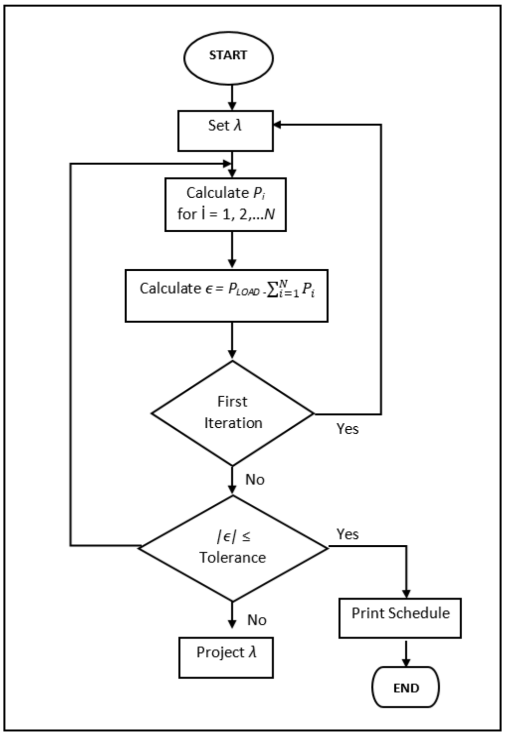

Fig. 1. Flow chart of a simplified Lambda Iteration Method

6. Calculation and Results

The fuel cost equation is first solved, independent of emission effects, using Lambda Iteration Method to find the total fuel cost of each generator set taken. Then, the emission equation is solved using Lambda Iteration Method. The two equations are then combined using weighting factors as shown in equation (14) to form the Combined Economic and Emission Dispatch function (CEED). The combined equation is then solved for two set of weighting factors to study the effect of emission on the fuel cost. The results are put in tabular form.

6.1. Three Generator System

Table 1 shows the values of cost coefficients (a_i,b_i,c_i) and emission coefficients (α_i,β_i,γ_i) and power limits for a three generator set. Table 2 shows the values of λ, output of each generator (the sum of which satisfies the total demand) and the fuel cost for three different demands to be fulfilled. Table 3 shows the power output of each generator in three generator set at W_1 = 0.3 and W_2= 0.7 when fuel cost equation and emission equation were combined. Tables 4 and 6 shows the effect of emissions on the fuel cost when both are made into single objective function using two combinations of Weighting Factors and total emissions of the 3 generator set. Table 5 shows the power output of each generator in three generator set at W_1 = 0.7 and W_2= 0.3.

Table 1. Cost coefficients, Emission coefficients, Power limits of three generator set

G	a_i	b_i	c_i	α_i	β_i	γ_i	P_{imin}	P_{imax}
1	0.005	2.45	105	0.0126	-1.355	22.983	20	200
2	0.005	3.51	44.1	0.01375	-1.249	137.370	15	150
3	0.005	3.89	40.6	0.00765	-0.805	363.704	18	180

Table 2. Output power, Lambda, Total fuel cost of three generator set

P_D (MW)	λ	P_1	P_2	P_3	F_T(₹/hr)
200	3.89	144	38	18	858.43
250	4.116	166.6	60.6	22.6	1058.19
300	4.286	183.3	77.3	39.3	1273.216

Table 3. Power output of Generator at W_1 = 0.3 and W_2 = 0.7 for CEED

P_D (MW)	λ	P_1	P_2	P_3
200	1.45	80.741	57.42	61.78
250	1.75	95.132	70.769	83.382
300	2.05	109.924	84.252	105.2

Table 4. Economic Dispatch Cost and Emissions under various load for 3 generator set at W_1 = 0.3 and W_2 = 0.7

P_D (MW)	Total fuel cost (₹/hr)	Total emissions(Kg/hr)
200	897.61	449.873
250	1100	475.704
300	1327.212	519.708

Table 5. Power output of Generator at W_1 = 0.7 and W_2 = 0.3 for CEED

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P_D (MW)	λ	P_1	P_2	P_3
200	2.89	110.194	53.48	36.48
250	3.119	125.77	68.243	55.99
300	3.343	141.34	82.99	75.649

Table 6. Economic Dispatch Cost and Emissions under various load for 3 generator set at W_1 = 0.7 and W_2 = 0.3

P_D(MW)	Total fuel cost (₹/hr)	Total emissions (Kg/hr)
200	870.220	481.136
300	1073.151	510.650
400	1284.558	558.205

6.2. Six Generator System

Table 7 shows the values of cost coefficients (a_i,b_i,c_i) and emission coefficients (a_i,β_i,γ_i) and power limits for a six generator set. Table 8 shows the values of λ, output of each generator (the sum of which satisfies the total demand) and the fuel cost for three different demands to be fulfilled. Table 9 shows the power output of each generator in six generator set at W_1 = 0.3 and W_2= 0.7 when fuel cost equation and emission equation were combined. Tables 10 and 12 shows the effect of emissions on the fuel cost when both are made into single objective function using two combinations of Weighting Factors and total emissions of the six generator set. Table 11 shows the power output of each generator in six generator set at W_1 = 0.7 and W_2= 0.3.

Table 7. Cost coefficients, Emission coefficients, Power limits of six generator set

G	a_i	b_i	c_i	α_i	β_i	γ_i	P_{imin}	P_{imax}
1	0.152	38.540	756.80	0.0042	0.3300	13.86	10	125
2	0.106	46.160	451.32	0.0042	0.3300	13.86	10	150
3	0.028	40.400	1050.00	0.0068	-5455	40.26	35	225
4	0.035	38.310	1243.53	0.0068	-0.5455	40.26	35	210
5	0.021	38.328	1658.57	0.0046	-0.5112	42.92	130	325
6	0.018	38.270	1356.66	0.0046	-0.5112	42.96	125	315

Table 8. Output power, Lambda, Total fuel cost of six generator set

P_D(MW)	λ	P_1	P_2	P_3	P_4	P_5	P_6	F_T (₹/hr)
500	43.83	17.411	10	61.304	78,09	178.690	154.533	24333.868
600	44.91	21.194	10	81.604	95.143	205.762	186.111	31426.524
700	46.13	21.153	10	81.610	95.140	205.75	186.101	35753.442

Table 9. Power output of Generator at W_1 = 0.3 and W_2 = 0.7 for CEED

P_D (MW)	λ	P_1	P_2	P_3	P_4	P_5	P_6
500	13.67	19.34	10	73.72	78.09	164.69	147.71
600	14.19	24.69	10	81.604	93.465	191.70	138.435
700	14.71	30.122	10	81.610	113.48	219.38	208.468

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Table 10. Economic Dispatch Cost and Emissions under various load for 6 generator set at W_1 = 0.3 and W_2 = 0.7

P_D (MW)	Total fuel cost (₹/hr)	Total Emissions (Kg/hr)
500	26923.371	270.226
600	29671.633	319.873
700	36010.323	470.824

Table 11. Power output of Generator at W_1 = 0.7 and W_2 = 0.3 for CEED

P_D (MW)	λ	P_1	P_2	P_3	P_4	P_5	P_6
500	30.88	17.69	10	63.85	79.973	177.53	152
600	31.75	21.7	10	83.95	96.36	205	183.11
700	31.6	25.14	10	103.59	112.37	231.96	216.51

Table 12. Economic Dispatch Cost and Emissions under various load for 6 generator set at W_1 = 0.7 and W_2 = 0.3

P_D (MW)	Total fuel cost (₹/hr)	Total Emissions (Kg/hr)
500	26883	280.5519
600	31443.03	370.210
700	35972.557	483.691

7. Result and Discussions

Three and six generator system was studied to find the variation of the fuel cost when emissions were added to the fuel equation.

Table 2 and Table 8 shows the fuel cost for three and six generator set respectively when emissions were not taken into consideration. Table 3 and Table 5 shows the value of fuel cost when the emissions were added to the fuel cost equations for three generator system and Table 10 and 12 shows the same for six generator system. On comparing the values of Fuel costs in the tables discussed above, it is seen that the fuel cost increases when the effect of emissions were added to the fuel cost equation.

Table 4 and Tables 6 shows the variations in the fuel cost and total emissions when the values of Weighting Factors were changed for three generator system and Table 10 and 12 shows the same for six generator system.

8. Conclusions

The fuel cost and emissions have been combined into a single objective function and tested for three and six generator system. Emissions, when added to the fuel cost equations increase the overall cost of the generator set.

The two objectives were combined using some Weighting Factor. The value of weighting factor decides the achievement of objective. Greater the value of Weighting Factor, less the corresponding value of fuel cost or emissions. On increasing the value of Weighting Factor, we decrease the value of corresponding fuel cost or emission and vice-versa.

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