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Differential Evolution Based Solution for Combined Economic and Emission Power Dispatch with Valve Loading Effect

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Abstract: In this work, a combination of Economic and Emission power dispatch optimization is solved by differential evolution technique using MAT-lab programming technique. The crux of the objective is to find the economic scheduling of the generation, such that the required load demands of the generation can be satisfied and the operation such as equality and inequality constraints of the generators including the total emissions within the allowable emission limit for satisfactory operation of the thermal power plant. In this work only one emission of Nitrogen oxide is considered for analysis. The economic / environmental load dispatch is analyzed in two cases. Case one deals excluding transmission losses and case two deals including transmission losses in the system. The standard data of IEEE Thirty Bus System and Indian Utility Sixty Two Bus Test System has been taken into account and simulated with aid of MAT-lab software and results are obtained. An apposite program has been developed using differential evolution technique and which has been verified for various load demand.

Keywords: Economic and Emission Dispatch, Valve Point Effect, Differential Evolution Technique, Indian Utility Sixty Two Bus System, IEEE Thirty Bus system, Mat Lab.

1. Introduction

Optimal generation dispatch represents one of the vital issues in power systems engineering. The optimal operating state reduces cost and improves overall system efficiency. For dispatching the electrical power by operating the units at minimum cost is not only the consideration, because of increasing environmental hazards. The main objective function of the environmentally constrained economic power dispatch problem is to reduce the emission rate and cost of generation. An efficient and reliable Differential Evolution programming based algorithm for finding the economic/environmentally power dispatch problem is presented. It is defined as a dual objective optimization problem with both equality and inequality constraints. The number of iterations is performed in a typical IEEE thirty bus systems and Indian utility sixty two bus system to achieve the objective function [1] & [2].

2. Economic Dispatch

A. Introduction

The primary requirement of power system optimal generation scheduling is to generate, at the possible lowest cost adequate quantity of power to satisfy the power demand. The problem of optimal generation scheduling can be formulated as minimization of the production cost function subjected to the various power system constraints along with power balance relation [3], [4], [5], [6] & [7].

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B. Objective Function

The traditional economic power dispatch problem is to reduce the total production cost by controlling the unit output of the each unit connected to the network. The overall production cost of the network is the summation of the fuel cost function of each generator as given in equation (1).

$$Min \sum F_i(P_{Gi}) \tag{1}$$

The overall \$/hr production cost function with valve loading effect of the generator can be expressed in equation (2) [8].

$$F_1 = \sum_{i=1}^{N} (a_i + b_i P_{Gi} + c_i P_{Gi}^2) + \left| d_i sin\left(e_i (P_{i\,min} - P_i)\right)\right| \$/h \tag{2}$$

Where

F_1 = Total fuel cost

a_i, b_i, c_i, e_i & d_i= Constants Coefficients of the i[th] unit

N = Number of generating units

P_i = Power output of i[th]generator

$P_{i.min}$= minimum power constraint for i[th] unit in MW

C. Equality Constraint

Equality constraint is also known as Power Balance Constraint. It is considered in two ways. Case one deals excluding transmission losses and case two deals including transmission losses in the system. In case one, balance is met when the sum of generation (ΣP_{Gi}) equals the sum of load, considering the system network as loss less as in equation (3).

$$\sum_{i=1}^{N} \boldsymbol{P_{Gi} - P_D = 0} \tag{3}$$

In case two, balance is met when sum of generation (ΣP_{Gi}) equals the sum of load (P_D) and total power losses (P_{Loss}), considering the power system network as including loss as stated below (4).

$$\sum_{i=1}^{N} \boldsymbol{P_{Gi} - P_D - P_{Loss} = 0} \tag{4}$$

The losses can be determined by using loss formula as function of the system generators outputs, as given (5).

$$P_L = \sum_{i=1}^{N_O} \sum_{j=1}^{N_O} P_{Gi} B_{ij} P_{Gi} + \sum_{i=1}^{N_O} P_{Gi} B_{io} + B_{oo} \tag{5}$$

Where

B_{ij}, B_{i0}, B_{00} = Loss Coefficients

N = Number of Generators

P_{Gi}= Power output of i[th]generator
P_D = Total demand
P_L = Power loss

D. Inequality Constraint

Inequality constraint is also known as power generator capacity constraint. Each generating units have minimum (P_{Gimin}) and maximum (P_{Gimax}) generation capacity according to its machine ratings. This can be constructed as an inequality constraint in equation (6).

$$P_{Gimin} \leq P_{Gi} P_{Gimax}$$
$$i = 1, \dots \dots N \tag{6}$$

Where
P_{Gimin} = Min power generated in i[th] generation
P_{Gimax}= Max power generated in i[th]generation

3. Environmental Load Dispatch

A. Introduction

According to the 1990 Clean Air Amendment, environmental considerations have regained considerable attentions in the power system industry due to the significant amount of emission and other pollutants derived from fossil based power generation. So there is a necessity of economic and emission power dispatch to reduce generation cost and emission rate. As the traditional the economic generation scheduling problem is to reduce the production cost without considering emission rate. The emission power dispatch problem is to reduce the emission output without considering economic constraints. So in order to overcome the above mentioned problem the new method of combination of economic and emission power dispatch technique is developed [9], [10], [11], [12] & [13].

The production of power from the fossil fuel generating units discharges several harmful gases, such as Sulfur Oxides (SO_2), Nitrogen Oxides (NO_x) and Carbon Dioxide (CO_2) into the environment. The combination of economic and emission power dispatch problem can be constructed as an optimization problem. The SO_2 and NO_x are the two major gases that are released from generating unit. So these two gases are considered for the emission dispatch. During the combustion process in a power station, some of the sulfur unites reacts with the oxygen in the fuel and combustion air to form SO_2 and that are released through the stack as an emission. The nitrogen combines with oxygen from the fuel to form fuel $NO_{x,}$ it also combines with oxygen from the air to form thermal NO_x. The total NO_x emission is a combination of the thermal and fuel NOx.

B. Multi-objective Economic/Environmental Dispatch Formulation

One of the techniques used to minimizing the emission production in a power station is the Economic and emission Power Dispatch. This dispatch finds the power allocation that reduces the generation cost of the system considering the amount of emission produced. Sulfur dioxide and NO_x emission is dependent on the power consumption. It is formulated as the traditional fuel cost function equation that comprises of polynomial and exponential terms as below

$$F_2 = \sum_{i=1}^{N} \left[10^{-12} \left(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 + \eta_i \, exp(\delta_i P_{gi}\right)\right] tons/hr \tag{7}$$

Where,
α_i, β_i, $\gamma_i \boldsymbol{\eta_i}$, $\boldsymbol{\delta_i}$= i[th] generation unit emission rate coefficients
F_2 = Total emission
N = Number of Generators

P_{Gi}= Power output of i[th]generator

The nature of cost and emission production allows the economic and emission dispatch problem which is constructed as a dual objective optimization problem.

C. Objective Function

The combination of economic and emission dispatch problem is to reduce the cost function and the emission function including penalty factor as in equations (8) and (9).

$$h = \frac{F_T(P_{i.min})/P_{i.min}}{E_T(P_{i.min})/P_{i.min}} \quad (8)$$

Where $P_{i.min}$is minimum power constraint for i_{th} unit in MW, Price penalty factor h (\$/lb)
Minimize $\emptyset_T = F_T(P) + h.E_T(P)$ (9)
Where
F_i (P_{Gi}) is a cost function
E_i(P_{Gi})is an emission function.

4. Differential Evolutiontechnique (DE)

A. Introduction

The differential evolution technique (DE) is a population based algorithm. The main stages are initialization, crossover, mutation and selection. In initialization stage the populations are generated. In the mutation process mutant vector are created based on difference of the randomly chosen target vector and added up with another target vector. In cross over stage cross over operator does the selection process. The final selection is done by calculating the fitness of the vector by the selection operator [14] & [15].

B. The Main Stages of the DE Technique

- *Initialization*

In this process initial population of candidates are generated by assigning values to the parameter of the each individual of the population as shown in equation (10). The assigning values should be within the lower and upper boundary limits.

$$X_{j,i}^{(0)} = X_j^{min} + \eta_j\left(X_j^{max} - X_j^{min}\right)\forall i, j \quad (10)$$

Where
$\eta_j$is a random uniformly distributed number.
X_j^{min}&X_j^{max} are lower and upper boundary constraints.

For certain problems, information might be available that would favors exploration in certain areas. In this case the population can be seeded around these areas of interest.

- *Mutation*

The mutation operation is performed on the each target vector to obtain the new parameter vectors called mutant vectors, as given in equation (11).

$$V = X_{r1,G} + F\left(X_{r2,G} - X_{r3,G}\right) \quad (11)$$

Where '*F*' is a scaling factor. Scaling factor is used to controls the amplification of the differential variation and to adjust the perturbation size in the mutation. It should be in the range of [0, 1].

- *Crossover*

The crossover operation is performed to create the trial vectors, which are used in the selection process. The mutant and target vector combines to form the trial vector. If the generated random number value is less or equal than the assumed value of the crossover constant, then the mutant vector is chosen, else parent vector is chosen as given in equations (12) and (13). The assumed crossover constant (*CR*) should be within the range of [0, 1].

$$U_i^G = [U_{i,1}^G, U_{i,2}^G, \ldots\ldots, U_{i,D}^G] \tag{12}$$

$$u_{i,1}^G = \begin{cases} v_{i,1}^G & if rand(\ \ ) \le CR \\ x_{i,1}^G & otherwise \end{cases} \tag{13}$$

- *Selection*

The population of the next generation is chosen by the selection operator in the selection process. In the selection process the operator compares the fitness of the trial vector and corresponding target vector, and chooses the best vector as mentioned in Equation (14).

$$X_i^{(G,1)} = \begin{cases} X_i^{"(G)} & if f(X_i^{"(G)} \le f(X_i^{(G)} \\ X_i^{(G)} otherwise \end{cases} \tag{14}$$

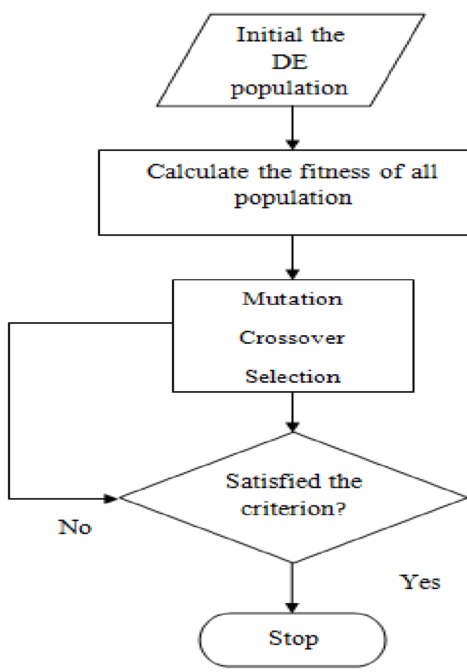

Figure 1. Flow chart for DE

This process is repeated for several iterations, until the individual improves their fitness of the optimal values. The flow chart for the DE algorithm is illustrated in figure 1.

5. Problem Formulation

A. IEEE 30 Bus Systems

The IEEE thirty bus system that comprises of six generators, 43 branches, and 21 load buses. The typical IEEE thirty bus system as shown in figure 2 is considered for the proposed approach. The system load is 450 MW. The fuel cost and emission coefficient data's are given in table 1 and 2.

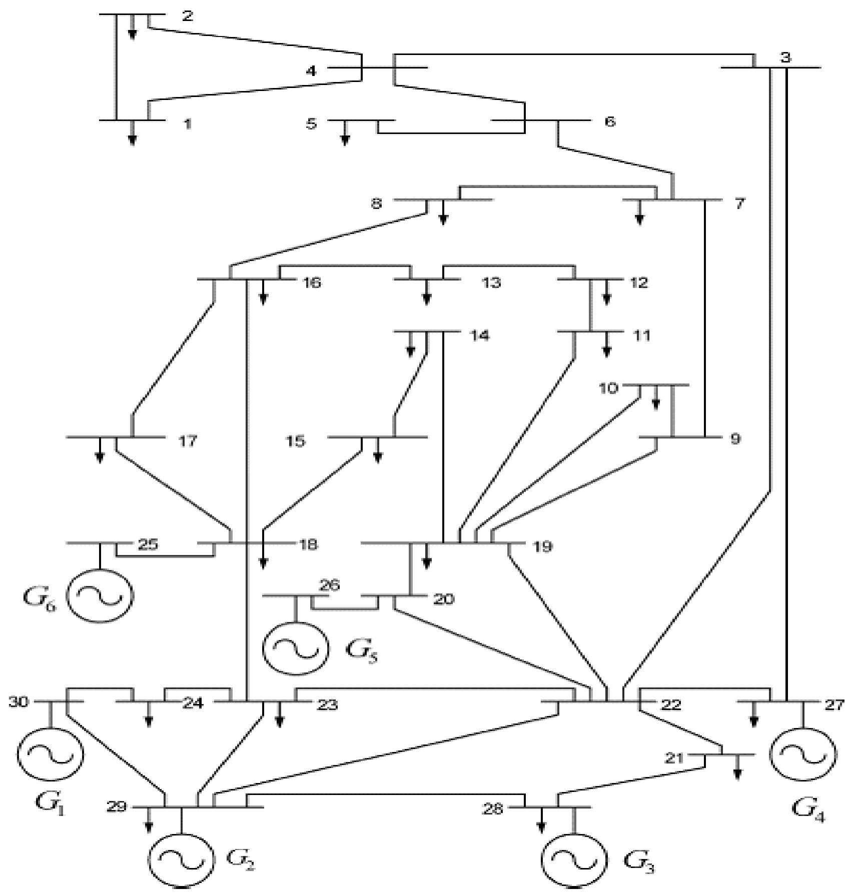

Figure 2. One line diagram for IEEE thirty bus systems

Table 1
Generator Cost Coefficients

Unit	Fuel Cost Coefficients					P_{Gimin}	P_{Gimax}
	a_i	b_i	c_i	d_i	e_i		
1	10	200	100	15	6.283	5	150
2	10	150	120	10	8.976	5	150
3	20	180	40	10	14.784	5	150
4	10	100	60	5	20.944	5	150
5	20	180	40	5	25.133	5	150
6	10	150	100	5	18.48	5	150

Table 2.
Emission Coefficients

Unit	Fuel Emission Coefficients					P_{Gimin}	P_{Gimax}
	α_i	β_i	γ_i	η_i	δ_i		
1	4.091	-5.554	6.490	0.0002	2.857	5	150
2	2.543	-6.047	5.638	0.0005	3.333	5	150
3	4.258	-5.094	4.586	0.000001	8.000	5	150
4	5.426	-3.550	3.380	0.002	2.000	5	150
5	4.258	-5.094	4.586	0.000001	8.000	5	150
6	6.131	-5.555	5.151	0.00001	6.667	5	150

A.1. Loss coefficient

The transmission loss depends on line currents and line resistances. It is represented as a function of plant loading. Loss coefficient depends on source voltage and power factors. The source voltage and power factor depends on and vary with system operating conditions. However B- coefficients are constants. It is sufficiently accurate to calculate B- coefficients for some average operating conditions and use these values for economical loading for all the load variations. However, for large load variations or for major systems, several sets of loss coefficients are used.

B COEFFICIENTS OF THE 6 GENERATOR STUDY

$$B = \begin{bmatrix} 0.1382 & -0.0299 & 0.0044 & -0.0022 & -0.0010 & -0.0008 & -0.0535 \\ -0.0299 & 0.0487 & -0.0025 & 0.0004 & 0.0016 & 0.0041 & 0.0030 \\ 0.0044 & -0.0025 & 0.0182 & -0.0070 & -0.0066 & -0.0066 & -0.0085 \\ -0.0022 & 0.0004 & -0.0070 & 0.0137 & 0.0050 & 0.0033 & 0.0004 \\ -0.0010 & 0.0016 & -0.0066 & 0.0050 & 0.0109 & 0.0005 & 0.0001 \\ -0.0008 & 0.0041 & -0.0066 & 0.0033 & 0.0005 & 0.0244 & 0.0015 \\ -0.0535 & 0.0030 & -0.0085 & 0.0004 & 0.0001 & 0.0015 & 0.000986 \end{bmatrix}$$

where

$$B = \left[\begin{array}{c|c} B_{ij} & B_{i0}/2 \\ \hline B_{i0}/2 & B_{00} \end{array} \right]$$

B. Indian Utility 62 Bus Test System

The Indian utility sixty two bus system that comprises of nineteen generators, 33 load buses. The typical Indian utility sixty two bus system as shown in figure 3 is considered for the proposed approach. The system load is 2908 MW. The fuel cost and emission coefficient data's are given in table 3 and 4.

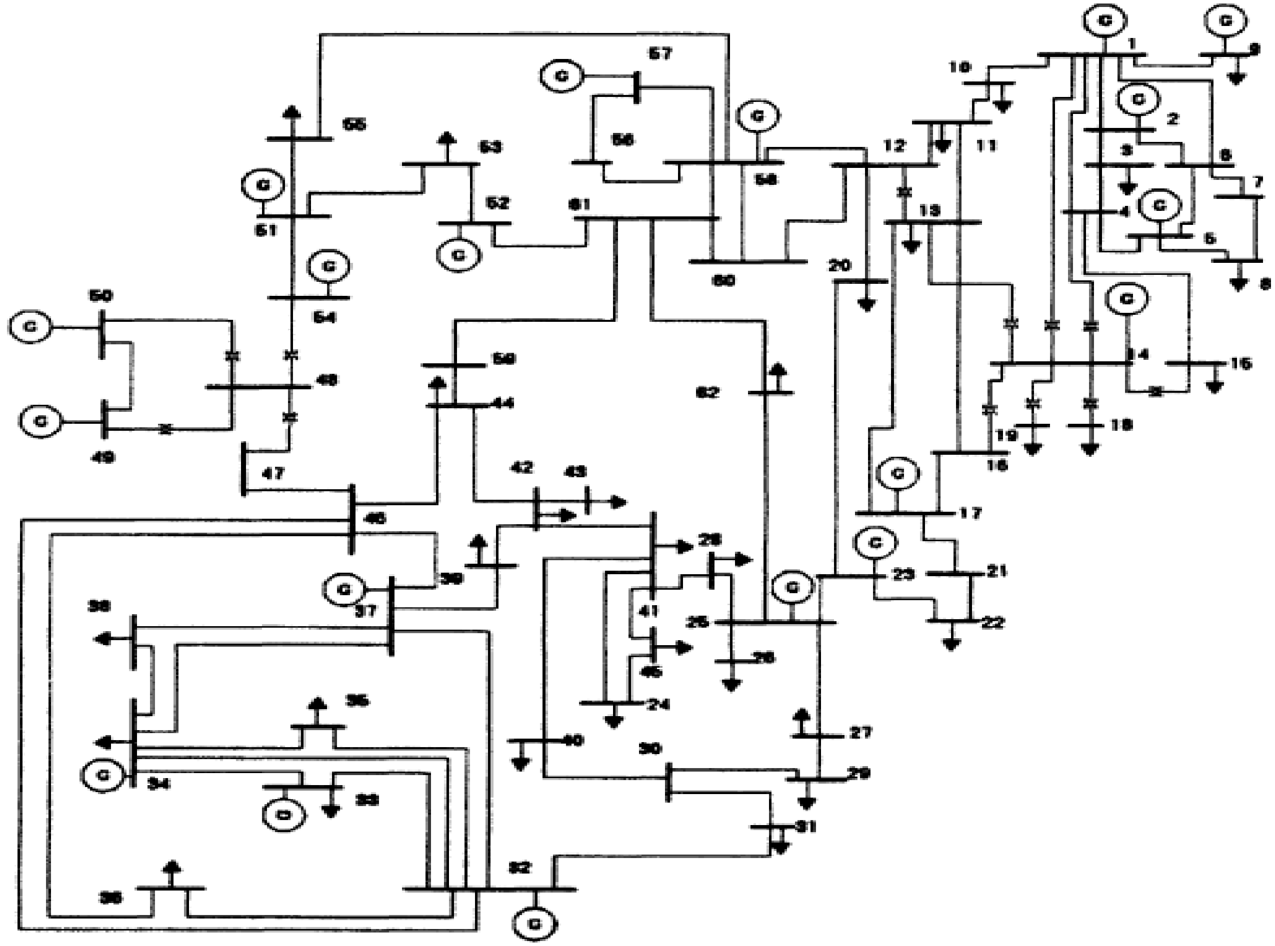

Figure 3. One line diagram for Indian Utility sixty two bus systems

Table 3.
Generator Cost Coefficients

Unit	Fuel Cost Coefficients					P_{Gimin}	P_{Gimax}
	a_i	b_i	c_i	d_i	e_i		
1	0.0097	6.8	119	90	0.72	100	300
2	0.0055	4	90	79	0.05	120	438
3	0.0055	4	45	0	0	100	250
4	0.0025	0.85	0	0	0	8	25
5	0	5.28	0.891	0	0	50	63.75
6	0.0080	3.5	110	0	0	150	300
7	0	5.439	21	0	0	50	63.75
8	0.0075	6	88	50	0.52	100	500
9	0.0085	6	55	0	0	200	600
10	0.0090	5.2	90	0	0	15	40
11	0.0045	1.6	65	0	0	50	150
12	0.0025	0.85	78	58	0.02	25	75
13	0	2.55	49	0	0	50	63.75
14	0.0045	1.6	85	0	0	0	95
15	0.0065	4.7	80	92	0.75	20	220
16	0.0045	1.4	90	0	0	15	80
17	0.0025	0.85	10	0	0	15	80
18	0.0045	1.6	25	0	0	50	230
19	0.0080	5.5	90	0	0	400	500

Table 4.
Emission Coefficients

Unit	Fuel Emission Coefficients			P_{Gimin}	P_{Gimax}
	α_i	β_i	γ_i		
1	0.0180	-1.81	24.300	100	300
2	0.0330	-2.5	27.023	120	438
3	0.0330	-2.5	27.023	100	250
4	0.0136	-1.3	22.070	8	25
5	0.0180	-1.81	24.300	50	63.75
6	0.0330	-2.5	27.023	150	300
7	0.0126	-1.36	23.040	50	63.75
8	0.0360	-3.00	29.030	100	500
9	0.0400	-3.20	27.050	200	600
10	0.0136	-1.30	22.070	15	40
11	0.0139	-1.25	23.010	50	150
12	0.0121	-1.27	21.090	25	75
13	0.0180	-1.81	24.300	50	63.75
14	0.0140	-1.20	23.060	0	95
15	0.0360	-3.00	29.000	20	220
16	0.0139	-1.25	23.010	15	80
17	0.0136	-1.30	22.070	15	80
18	0.0180	-1.81	24.300	50	230
19	0.0400	-3.00	27.010	400	500

6. Result

Two different cases are considered, in all the cases corresponding graph for iteration vs. cost are shown below.

A. For IEEE 30 bus system
CASE1: Without Penalty Factor

- *Without loss*

For comparison purpose, in the first case the system is considered as lossless and without penalty the corresponding cost and iteration is plotted as below.

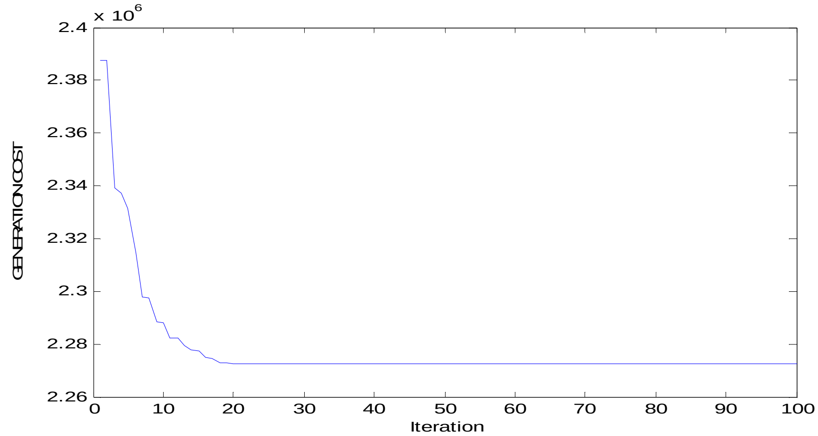

Figure 4. Iteration Vs Cost

- *With loss*

For comparison purpose, in the second case the system is considered as loss and without penalty the corresponding cost and iteration is plotted as below.

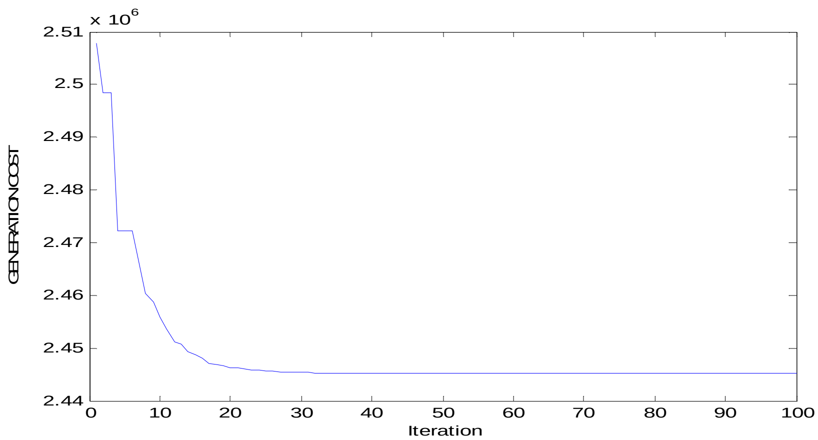

Figure 5. Iteration Vs Cost

Table 5.
Output Result for Case 1 (Without penalty factor)

Generation (MW)	Without loss and without penalty	With loss and without penalty
PG1	57.732	46.2460
PG2	52.232	29.0841
PG3	110.846	128.1965
PG4	91.964	112.1850
PG5	102.912	110.9582
PG6	38.023	38.8605
Cost($/hr)	2.3007e+006	2.4452e+006
Emission(ton/hr)	1.2966e+208	1.1723e+224
Loss	-	6.0119

Without considering the penalty, the Cost and Emission of the system with and without losses are given in Table V.

CASE2: With Penalty Factor

- *Without loss*

For comparison purpose, in the third case the system is considered as lossless and with penalty the corresponding cost and iteration is plotted as below.

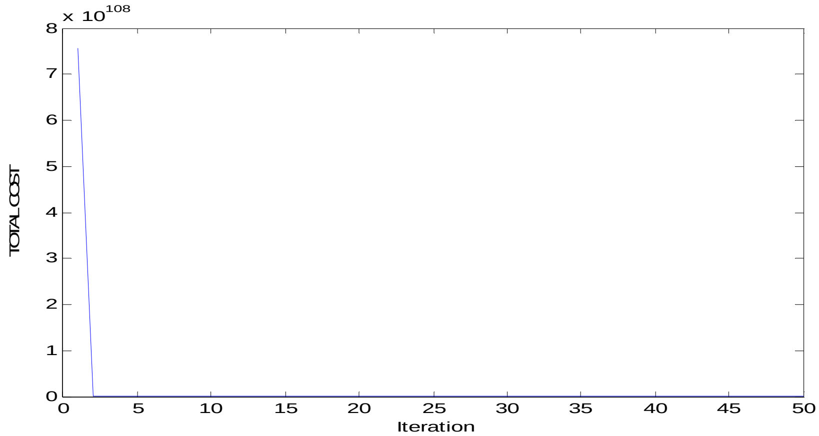

Figure 6. Iteration Vs Cost

- *With loss*

For comparison purpose, in the third case the system is considered as lossless and with penalty the corresponding cost and iteration is plotted as below.

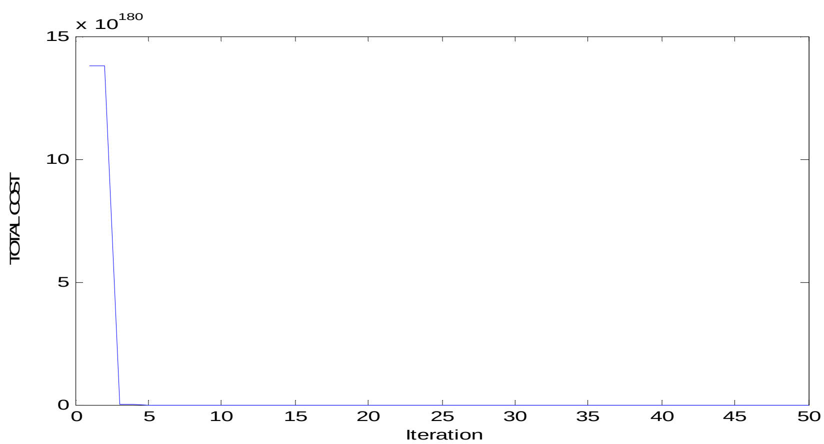

Figure 7. Iteration Vs Cost

With considering the penalty, the Cost and Emission of the system with and without losses are given in Table 6

Table 6.
Output Result for Case 2 (With penalty factor)

Generation(MW)	Without loss and with penalty	With loss and with penalty
PG1	76.7449	101.4606
PG2	64.9060	105.6230
PG3	107.2734	45.7802
PG4	112.4717	127.8623
PG5	40.1761	45.8352
PG6	60.2666	54.0100
Cost($/hr)	2.8136e+006	3.8823e+006
Emission(ton/hr)	4.9031e+096	7.2255e+156
Loss	-	16.2814
$\emptyset_T$	4.5111e+094	1.0139e+146

B. For Indian Utility 62 bus system

Two different cases are considered, in all the cases corresponding graph for iteration vs. cost are shown below. The system load demand is 2908 MW.

CASE1: Without Penalty Factor

- *Without loss*

For comparison purpose, in the first case the system is considered as lossless and without penalty the corresponding cost and iteration is plotted as below.

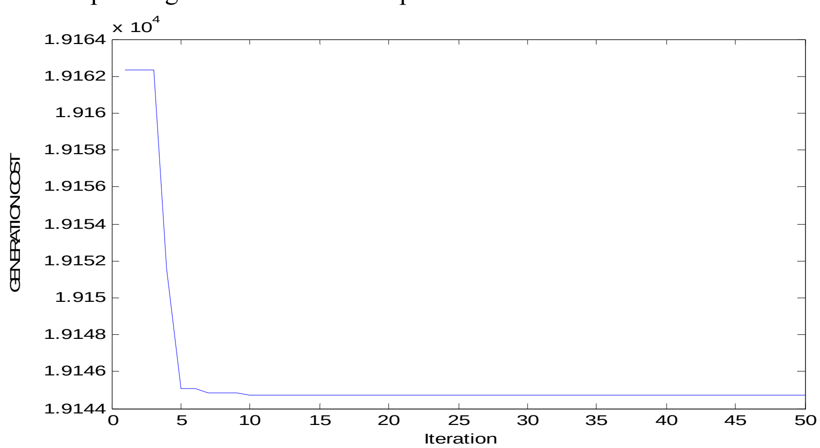

Figure 8. Iteration Vs Cost

- *With loss*

For comparison purpose, in the second case the system is considered as loss and without penalty the corresponding cost and iteration is plotted as below.

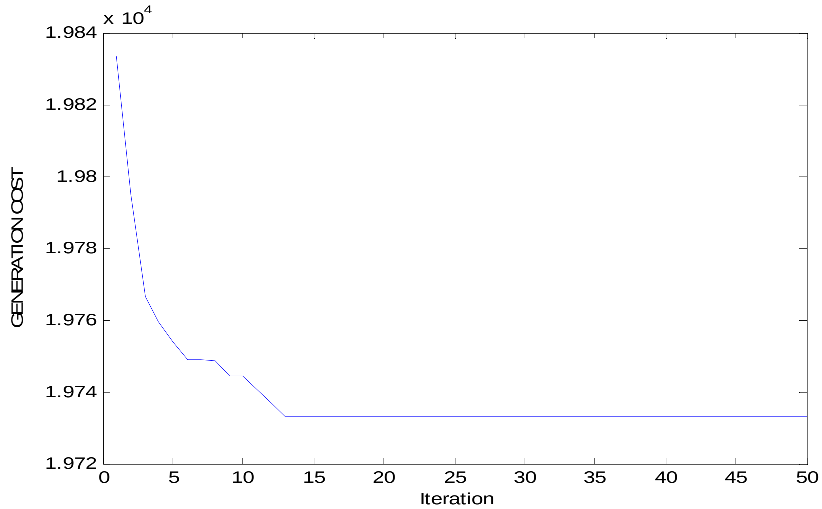

Figure 9. Iteration Vs Cost

Table 7.
Output Result for Case 1 (Without penalty factor)

Generation (MW)	Without loss and without penalty	With loss and without penalty
PG1	252.321	213.402
PG2	393.568	423.999
PG3	238.493	190.934
PG4	018.925	017.099
PG5	055.486	055.679
PG6	272.614	195.638
PG7	060.948	058.261
PG8	240.375	276.436
PG9	211.562	319.644
PG10	014.693	027.547
PG11	077.569	104.511
PG12	067.490	057.010
PG13	061.250	053.468
PG14	031.016	041.140
PG15	185.308	188.547
PG16	079.799	066.165
PG17	077.811	035.876
PG18	142.929	184.064
PG19	431.501	427.874
Cost($/hr)	1.9145e+004	1.9733e+004
Emission(ton/hr)	1.7471e+004	1.8282e+004
Loss	-	20.9467

Without considering penalty, the Cost and Emission of the system with and without losses are given in table 7.

CASE2: With Penalty Factor

- *Without loss*

For comparison purpose, in the third case the system is considered as lossless and with penalty the corresponding cost and iteration is plotted as below.

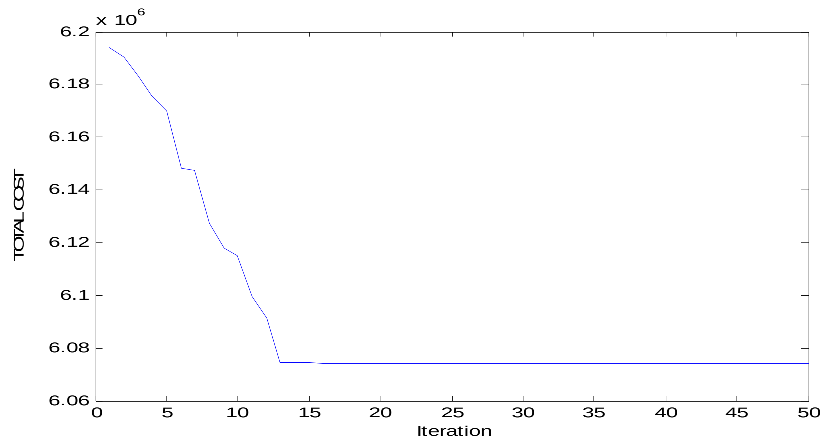

Figure 10. Iteration Vs Cost

- *With loss*

For comparison purpose, in the third case the system is considered as lossless and with penalty the corresponding cost and iteration is plotted as below.

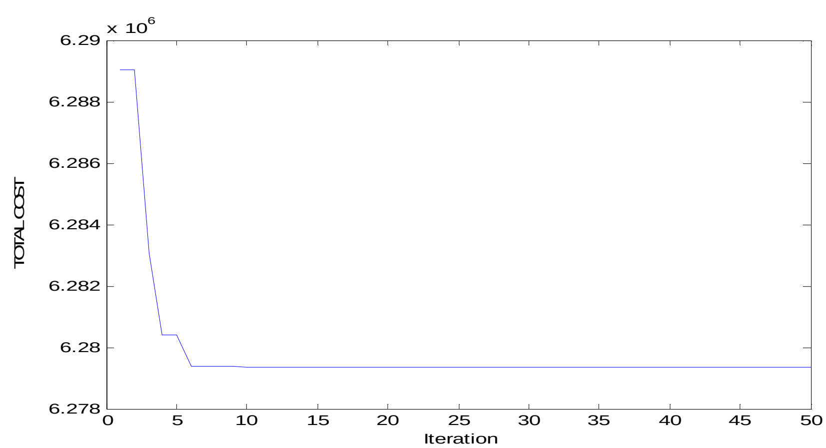

Figure 1. Iteration Vs Cost

Table 8.
Output Result for Case 2 (With penalty factor)

Generation (MW)	**Without loss and with penalty**	**With loss and with penalty**
PG1	243.469	262.8861
PG2	193.785	381.728
PG3	192.901	218.867
PG4	012.922	019.217
PG5	058.521	063.591
PG6	260.426	229.683
PG7	050.558	062.633
PG8	275.139	248.874
PG9	411.811	368.215
PG10	024.238	037.816
PG11	098.717	118.515
PG12	048.614	067.440
PG13	061.582	058.330
PG14	050.983	060.560
PG15	173.206	132.126
PG16	040.965	075.562
PG17	073.978	046.962
PG18	224.883	061.522
PG19	416.142	415.444
Cost($/hr)	1.9807e+004	2.0045e+004
Emission(ton/hr)	1.8034e+004	1.8644e+004
Loss	-	20.9467
$\emptyset_T$	6.0743e+006	6.2793e+006

With considering penalty, the Cost and Emission of the system with and without losses are given in table 8.

7. Result Discussion
For the IEEE 30 Bus System
CASE 1: *Including and Excluding Penalty Factor and Losses*

- *Generation Cost*

For the case without penalty Factor excluding and including loss the generation cost found out is 2.30e+06 $/hr and 2.45e+06 $/hr .For the case with penalty Factor excluding and including loss the generation cost found out is 2.81e+06 $/hr and 3.88e+06 $/hr.

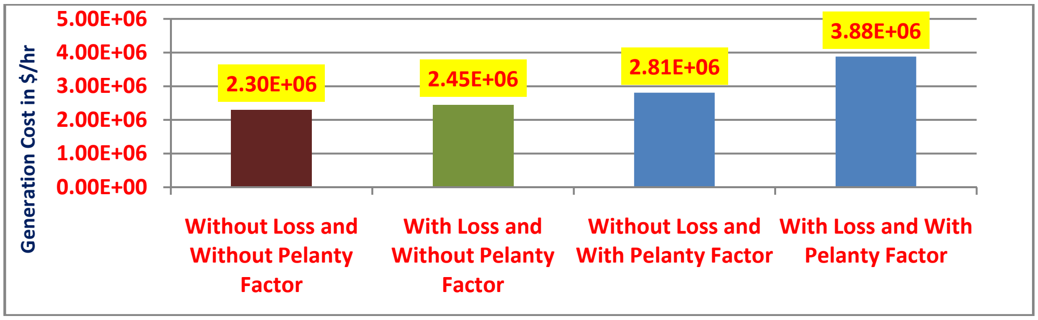

Figure 12. The Generation Cost Comparison for different cases for IEEE 30 bus System

- *Emission*

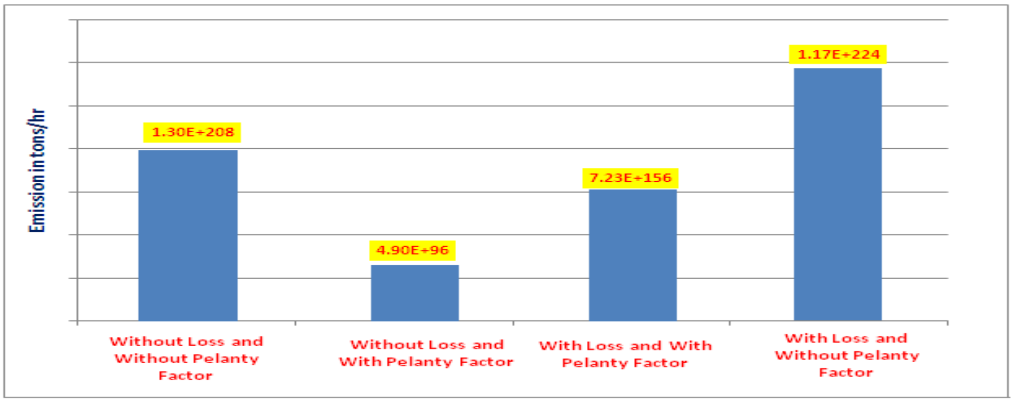

Figure 13. The Emission Comparison for Various Cases for IEEE 30 bus System

For the case without penalty Factor excluding and including loss the emission is 1.3e+208 tons/hr and 1.1723e+224 tons/hr. For the case with penalty Factor excluding and including loss the emission is 4.90e+96 tons/hr and 7.23e+156 tons /hr.

For The Indian Utility 62 Bus System
CASE 2. *Including and Excluding Penalty Factor and Losses*

- *Generation Cost*

For the case without penalty Factor excluding and including loss the generation cost found out is 1.91e+04 $/hr and 1.97e+04 $/hr. For the case with penalty Factor penalty Factor excluding and including loss the generation cost found out is 1.98 e+04 $/hr and 2.00e+04 $/hr.

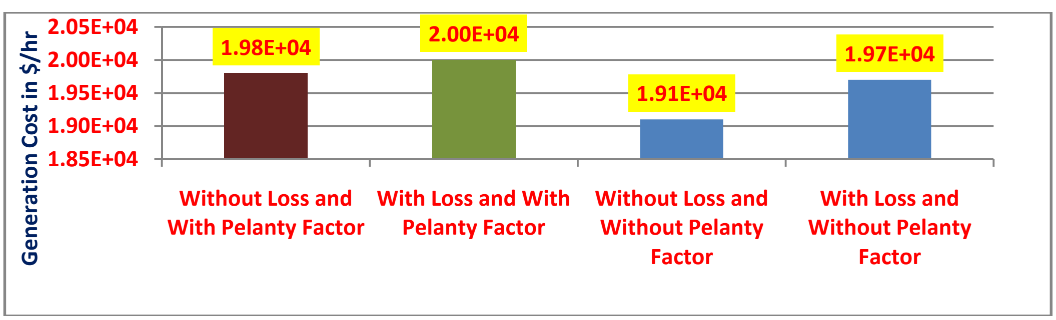

Figure 14. The Generation Cost Comparison for various cases for 62 bus Indian Utility System

- *Emission*

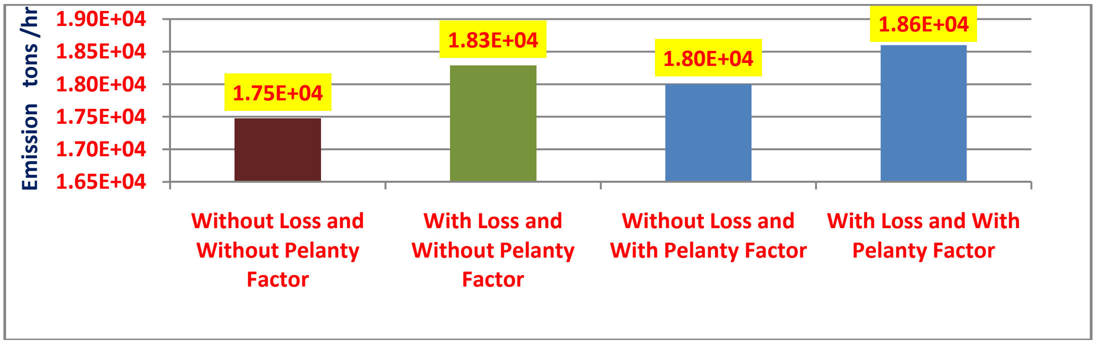

Figure 15. The Emission Comparison for various cases for 62 bus Indian Utility System

For the case without penalty Factor excluding and including loss the emission is 1.75e+04 tons/hr and 1.83e+04 tons/hr. For the case with penalty Factor excluding and including loss the emission is 1.80e+04 tons/hr and 1.86e+04 tons/hr.

8. Conclusion

In this work, DE algorithm based technique is used for determining the combined economic and emission power dispatch problem. The problem is defined as a dual objective optimization problem, to reduce the production cost and emission rate. Two different cases are considered, first one is based upon the system without transmission losses including and excluding penalty factor and second case deals with the system including transmission power losses including and excluding penalty factor. The proposed work is tested in typical IEEE thirty bus test system and Indian utility sixty two bus system. Several iterations were carried out on a typical system and the results are shown.

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