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Network Constrained Economic and Emission Dispatch Using Differential Evolution Algorithm

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Abstract

Economic Emission dispatch (EED) procedure involves the allocation of total generation requirements for the available generating units in the power system in a manner that the constraints imposed on different system variables are adequately satisfied and also minimum cost is achieved. Besides electrical energy power plants also produce sizeable quantities of solid waste sludge and pollutants that affect air and water quality. The pollutants affecting air quality are of the greatest interest that includes namely NO_X, CO_X, SO_X and other sundry oxides that can travel over considerable distance and have long term effects both in space and time. In general a large scale system that possesses multiple objectives. Objectives to be achieved namely economic operation, reliability, security and minimal impact on environment. In this paper solving highly non linear, stochastic economic emission dispatch with transmission loss coefficient. Differential Evolution (DE) algorithm is used to solve this highly non liner problem. Standard 3 and 6 generating units are considered to validate the performance of DE, which provides global optimum solution at fast convergence.

Key words: Economic dispatch; Emission Coefficient, Differential Evolution

Introduction

Economic Emission dispatch problem is to determine the optimal combination of generating power output for all generating units which will minimize the total fuel cost at the same time fulfilling total load, operational constraints and also minimal impact on environment [1]. The presence nonlinearities such us equality and non equality constraints in practical generator operation makes solving the ED problem becomes more complex, non-linear and more challenging. In addition to the ED objective, environmental aspects that arise from the emission produced by fossil fuel electric power plants become a foremost crisis to be addressed. The generation of electricity from fossil fuel releases several contaminants, such as Sulphur Oxides (SOx), Nitrogen Oxides (NOx) and Carbon Dioxide (CO2) into atmosphere [2]. Optimal load allocation of various generating units of the plants may lead to increase in the operating cost of the generating units. So, it is essential to find out a way which gives a balanced outcome between emission and cost can be obtained by Economic Emission Dispatch (EED) problem.

A variety of optimization methods are being carried out to facilitate a significant reduction in the Operational cost. Traditional techniques such as Lambda Iteration method [3], dynamic programming [4], mixed integer programming [5], branch and bound [6], gradient-based method, [7] and Newton's method [8] were used to achieve best possible dispatch to the EED problems.

In lambda iteration and gradient based methods cost functions are in terms of single quadratic function. These conventional [3-8] techniques are piecewise linear and monotonically increasing to locate the global best solution. [9].

Limitations of conventional methods were overcome by meta-heuristic approaches like Artificial Neural Networks (ANN) [10], Genetic Algorithms (GA) [11], Tabu Search (TS) [12], Simulated Annealing (SA) [13], Particle Swarm Optimization (PSO) [14], Although these methods due to curse of dimensionality with large computational problems these methods are not competent in accomplish global optimal solutions to the EED problems, to a great amount these methods may generate near optimal solutions. One of the most successful optimization technique proposed by Storm and Prince is Differential Evolution (DE) [15]. DE is proves to be a dependable and consistent in non-linear and multi-dimensional problems. DE has shown to be successful for constrained optimization problems [16].

In this paper, a DE method is applied for solving the EED problem for standard 3 and 6 thermal generating units is proposed. The each section of this paper is structured as follows. Section 2 discusses the EED problem formulation. Section 3 discusses the DE formulation. The proposed DE formulation is presented in section 4. The numerical results for 3 and 6 generating units with emission coefficients are presented in section 6. The conclusion of the paper is drawn in section 7.

Problem Formation

In the optimization problem formation, two important objectives in an electrical thermal power system are considered. These are economy and environmental aspects. The optimization problem is defined as [17],

$$\min\left[F_i(P_i), E_i(P_i)\right] \quad (1)$$

where

$F_1(P_i)$ Cost function of i^{th} generator in \$/hr

$E_i(P_i)$ Emission function of i^{th} generator in kg/hr

$$F_i(P_i) = \sum_{i=1}^{n} a_i P_i^2 + b_i P_i + c_i \tag{2}$$

where

a_i, b_i, c_i Fuel cost coefficients of i^{th} generator

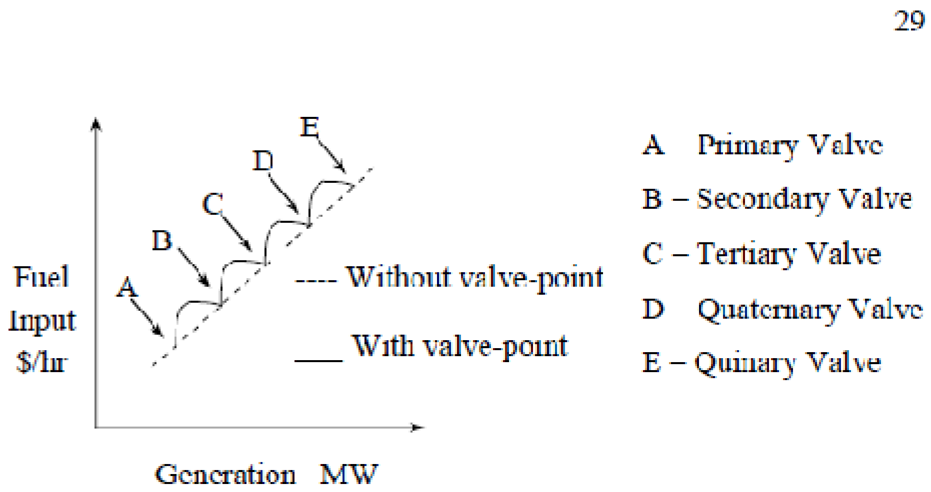

Figure 1: Fuel Cost Curve of Generating Unit

In normal generation of output power is varied continuously, smoothly, instantaneously and boundlessly. However, operating range of generators is restricted due to their mechanical and electrical characteristics, such as ramp rate limits, prohibited zones and bounded power. Hence, these constraints also to be considered for true economic operation. The operation limits and constraints in this problem are listed below.

There are several ways to include emission into the problem of economic dispatch. Reference19 summarizes the various algorithms for solving environmental dispatch problem with different constraints. One way of approach is to take account of the reduction of emission as an objective. In this paper, NO_X reduction is taken into account. Since NO_X is a major issue at the global level. A price penalty factor (*h*) is used in the objective function to combine the fuel cost, $/hr and emission functions, kg/hr of quadric form. The economic emission dispatch problem can be formulated as [17],

$$E_i(P_i) = \sum_{i=1}^{n} d_i P_i^2 + e_i P_i + f_i \tag{3}$$

d_i, e_i, f_i Fuel cost coefficients of i^{th} generator

Fuel cost can be determined as,

$$\phi_i = \sum_{i=1}^{n} (a_i + hd_i) P_i^2 + (b_i - he_i) P_i + (C_i + f_i) \tag{4}$$

$$h_i = \frac{F_i(P_{i\max})}{E_i(P_{i\max})} \tag{5}$$

Subject To Constraints

Equality Constraints

The equality constraint is the total real power generations from various generating units must meet the required power demand plus transmission losses of electrical network [18].

$$\sum_{i=1}^{n} P_i = P_D + P_L \tag{6}$$

where,

P_D Total demand in MW

P_L Transmission loss in MW

Power plants are geographically spread out; hence transmission loss must be taken into account to achieve true economical operation of generation. The network loss can be formulated using $B - Loss$ coefficients as given below

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{0i} P_i + B_{00} \tag{7}$$

where,

B_{ij}, B_{0i}, B_{00} Transmission loss B-coefficients

Equality constraint

Bounded Power Limits

The real power out of each generator should be within the minimum and maximum generating limits, which is given below,

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{8}$$

where,

$P_i^{\min}$ Lower limit of i^{th} generator

$P_i^{\max}$ Upper limit of i^{th} generator

Differential Evolution (DE) Algorithm

Differential Evolution (DE) algorithm is a population based stochastic optimization. DE is simple algorithm but has powerful features which make an attractive numerical optimization. In 1995 Storn and Price developed DE algorithm which was successfully applied to optimization of well known non-linear, non-differentiable and non - convex optimization problem [17]. DE merges arithmetic functions with standard functions of recombination, mutation and selection to evolve from randomly chosen parameter vectors.

Generation of Initial Population

The key parameters like population size, boundary constraints of optimization variables, mutation factor, crossover rate and stopping criterion. These key parameters controls DE algorithm which are to be selected by the user.

In DE, the real power output of all generators is represented as the population. In this paper, $(P_{i1}, P_{i2}, ..., P_{ij})$ is represented as a vector of chromosome to the solution of the ED problem. Initialization of N individual population is generated using

$$P_{ij} = P_i^{\min} + rand(\ )\left(P_i^{\max} - P_i^{\min}\right) \tag{9}$$

where

P_{ij} is the randomly generated number for the i^{th} generator in j^{th} population and $rand(\ )$ is a random number in the range of 0 - 1. Repeat Eq. (7) j times and produces the vector. Repeat the above procedure j times to create the j uniformly distributed individuals as initial feasible solutions in the search space. The resultant matrix after Eq. (9) is repeated ij^{th} times give the initial population as

$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & \cdots & P_{1j} \\ P_{21} & P_{22} & \cdots & \cdots & P_{2j} \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ P_{i1} & P_{i2} & \cdots & \cdots & P_{ij} \end{bmatrix} \tag{10}$$

Evaluating Individual Population

The goal is to minimize the fuel cost along with emission reduction. The fuel cost values and the fitness value of all the generated individuals are calculated using Eq. (1). The reduction of emission for the entire generated individual are calculated using Eq. (2). If any individual in the population is compared and ranked against all other individuals, then the fitness value of chosen individual quantifies as the optimum solution.

Mutation

Mutation is an operation that adds a differential vector to a population vector of individuals using anyone of the available mutation strategy in the DE algorithm. In this paper, the following mutation strategies are applied to the chosen generating units.

Mutation strategy 1

$$Z_{ij} = P_{R_1 j} + f_m\left(P_{R_2 j} - P_{R_3 j}\right) \tag{11}$$

Mutation strategy 2

$$Z_{ij} = P_{Bj} + f_m\left(P_{R_1 j} - P_{R_2 j}\right) \quad (12)$$

where,

f_m is the mutation factor and is a real value between the range [0.4, 1] controls the amplification of the difference between two population vector to stop stagnation. R_1, R_2 and R_3 are randomly selected mutually different integers that are different from the population index. Z_{ij} is the population vector of individual according to Eq. (11) and Eq.(12) P_{Bj} is the best performing vector of the current generation.

Recombination

Recombination one of the classical operator is performed next to the mutation. The trial vector is generated using recombination operation in which certain parameters in the target vector is replaced by the corresponding parameters in the randomly generated vector. The recombination strategy applied in this paper is

$$U_{ij} = \begin{cases} Z_{ij} & \text{if } R_{ij} \geq \text{CR} \\ P_{ij} & \text{Otherwise} \end{cases} \quad (13)$$

Where,

R_{ij} is the random number between the range [0, 1] .

CR is the set crossover rate or recombination rate within the range [0, 1].

U_{ij} is the recombination vector applied to the population according to Eq. (13).

Selection Operation

In this operation, better offspring from the initial population to the next generation is generated. The selection operation used in this paper can be decided as a type of tournament selection. In the tournament selection, the two randomly selected chromosomes from the previous operation are played and better chromosome is selected for the next operation. Chromosomes after the recombination and the corresponding chromosome in the initial population are played and the better chromosome is selected for the next generation in the selection operation used. The selection operation is given below,

$$P_{ij}^{*} = \begin{cases} U_{ij} & \text{if } f\left(U_{ij}\right) < f\left(P_{ij}\right) \\ P_{ij} & \text{Otherwise} \end{cases} \quad (14)$$

where,

$f\left(U_{ij}\right)$ is the generation cost of chromosome U_{ij} .

$f\left(P_{ij}\right)$ is the generation cost of chromosome P_{ij} .

If the Eq. (14) is repeated for number of population, the resultant P_{ij}^{*} can be taken as the initial population for the next generation.

Stopping Criterion
The sections 3.2 to 3.6 are repeated till the stopping criterion is met. The stopping criteria applied is the maximum number of generation.

Implementation of DE Algorithm To EED Problem

Step 1 : Read the required initial data fuel cost function constants, a_i, b_i, c_i, boundary conditions $P_i^{\min}$ and $P_i^{\max}$, number of generator n, population size i, number of generation t, mutation factor f_m, cross over parameter CR, probability distribution factor p and stopping criterion $t_{\max}$

Step 2 : Initialization: Population P_{ij} is the randomly generated number for the i^{th} generator in i^{th} population by using Eq. (9).

Step 3 : Evaluate the fitness function for each individual P_{ij} by using Eq. (1). and Eq. (2).

Step 4 : Mutation operation: Generate R_1, R_2, and R_3 uniform random variable with [0,1]. Perform mutation generate the individual Z_{ij} by using Eq. (11). and Eq. (12).

Step 5 : Recombination: Set initial cross over rate CR as 0.5, generate R of uniform random variable [0,1] for the population size i, perform the recombination by using Eq. (13).

Step 8 : Selection: Better chromosome $P_{B_{ij}}$ is selected for the next operation by using Eq.(14)

Step 9 : Update the individual P_{ij} .

Step 10 : Stopping criterion: Step 2 to Step 8 is repeated till the stopping criterion $t_{\max}$ is met.

Numerical Results and Discussions

In this section, the performance and effectiveness of the DE is illustrated with 3 and 6 thermal generating units with network losses for economic emission dispatch. All the programs were run on a 3.2 GHz Pentium IV processor with 2 GB RAM. In this simulation, DE method uses the sensitive parameters such as cross overrate CR, mutation factor f_m and probability distribution p , initial values to the following parameters are assigned from the experiences of many experiments [19].

- Population size i = 100
- Total number of Generation for 3 and 6 units $t_{\max}$ = 500
- Cross over rate $CR = 0.9$
- Mutation factor $f_m = 0.5$

Case I: 3-unit generating systems

Case I considers 3 thermal generating units with generating capacity and cost coefficients are given in table 1 [20] is taken as test system. NO_x coefficients of 3 thermal generating units are given in Table 2. The load demand for the test system is 400 MW, 500MW and 700 MW respectively and the loss coefficients B with 100 – MVA base capacity is given in Table 3. The proposed DE algorithm is applied to the test system for 100 test runs with 500 numbers of generations. Table 4 compares the result obtained from the DE is compared SGA, RGA and ABC. Form the comparison it shows that the proposed DE proves optimal solution the optimal dispatch of 3 thermal generating units are shown in Table 5. Convergence of the 6 units system is shown in Fig 2.

Table 1: Generating Capacity and Cost Coefficient of 3-Generating Units

Units	P_i^{min} (MW)	P_i^{max} (MW)	a_i (\$/MW^2)	b_i (\$/MW)	c_i (\$)
1	35	210	0.03546	38.30553	1243.53110
2	130	325	0.02111	36.32782	1658.56960
3	125	315	0.01799	38.27041	1356.65900

Table 2: Generating capacity and NO_X emission coefficient of 3-generating units

Units	P_i^{min} (MW)	P_i^{max} (MW)	d_i (\$/MW^2)	e_i (\$/MW)	f_i (\$)
1	35	210	0.00689	-0.5455	40.26690
2	130	325	0.00461	-0.5116	42.89553
3	125	315	0.00461	-0.5116	42.89553

Table 3: B- coefficient of 3-generating units

$$B_{ij} = \begin{matrix} 0.000070 & 0.000025 & 0.000030 \\ 0.000030 & 0.000069 & 0.000032 \\ 0.000025 & 0.000032 & 0.000080 \end{matrix}$$

Table 4: Comparison results of 3-generating units

Demand MW	Performance	Conventional Method [21]	SGA [21]	RGA [21]	ABC [20]	**DE**
400	Fuel Cost $/hr	20898.83	2083.54	20801.8	20838	**20780.08**
	Emission Kg/hr	201.5	201.35	201.25	200.22	**199.377**
	Loss MW	7.41	7.69	7.39	7.2	**6.0179**
500	Fuel Cost $/hr	25486.6402	25474.5	25491.6	25495	**25425**
	Emission Kg/hr	312	311.89	311.33	311.15	**309.0796**
	Loss MW	11.88	11.80	11.70	11.69	**10.05**
700	Fuel Cost $/hr	35485.05	35478.4	35471.4	35464	**35447.63**
	Emission Kg/hr	652.55	652.05	651.60	651.577	**650.218**
	Loss MW	23.37	23.29	23.28	23.36	**21.805**

Table 5: Optimum results of 3-generating units

Power Demand MW	P_1 (MW)	P_2 (MW)	P_3 (MW)	Loss (MW)	Total Generation (MW)
400	104.9685	157.4119	143.6374	6.0179	406.0179
500	129.8598	188.9536	191.2366	10.05	510.05
700	197.0142	267.0533	257.7381	21.8055	721.8056

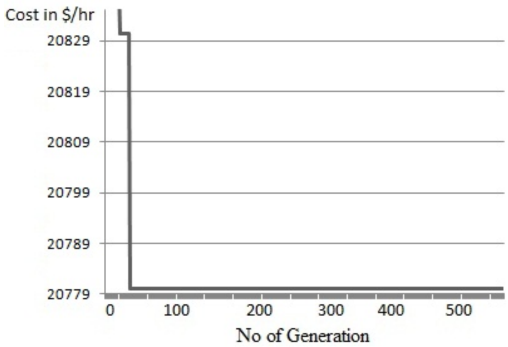

Figure 2: Convergence curve of 6 generating unit

Case II: 6-Unit Generating Systems

Case I considers 3 thermal generating units with generating capacity and cost coefficients are given in table 6 [20] is taken as test system. NO_x coefficients of 3 thermal generating units are given in Table 7. The load demand for the test system is 500MW and 900 MW respectively and the loss coefficients B with 100 – MVA base capacity is given in Table 8 The proposed DE algorithm is applied to the test system for 100 test runs with 500 numbers of generations. Table 9 compares the result obtained from the DE is compared SGA, RGA and ABC. Form the comparison it shows that the proposed DE proves optimal solution the optimal dispatch of 3 thermal generating units are shown in Table 10. Convergence of the 6 units system is shown in Fig 3.

Table 6: Generating capacity and cost coefficient of 6-generating units

Units	P_i^{min} (MW)	P_i^{max} (MW)	a_i ($/MW^2)	b_i ($/MW)	c_i ($)
1	10	125	0.15247	38.53973	756.79886
2	20	150	0.10587	46.15916	451.32513
3	35	225	0.02803	40.39655	1049.9977
4	35	210	0.03546	38.30552	1243.5311
5	130	325	0.02111	36.32782	1658.5596
6	125	325	0.01799	38.27041	1356.6592

Table 7: Generating capacity and NO_X emission coefficient of 6-generating units

Units	P_i^{min} (MW)	P_i^{max} (MW)	d_i ($/MW^2)	e_i ($/MW)	f_i ($)
1	10	125	0.00419	0.32767	13.85932
2	20	150	0.00419	0.32767	13.85932
3	35	225	0.00683	0.54551	40.2669
4	35	210	0.00683	0.54551	40.2669
5	130	325	0.00461	0.51116	42.89553
6	125	325	0.00461	0.51116	42.89553

Table 8: B- coefficient of 3-generating units

B_{ij} =	0.002022	-0.000286	-0.000534	-0.000565	-0.000545	0.000103
	-0.000286	0.003243	0.000016	-0.000307	-0.000422	-0.000147
	-0.000533	0.000016	0.002085	0.000831	0.000023	-0.000270
	-0.000565	-0.000307	0.000831	0.001129	0.000113	-0.000295
	-0.000454	-0.000422	0.000023	0.000113	0.000460	-0.000153
	0.000103	-0.000147	-0.000270	-0.000295	-0.000153	0.000898

Table 9: Comparison Results of 3-Generating Units

Demand MW	Performance	Conventional Method [21]	HGA[21]	ABC [21]	**DE**
500	Fuel Cost $/hr	27638.3	27695	27613	**27613**
	Emission Kg/hr	262.454	263.37	263.012	**263.00**
	Loss MW	8.830	10.135	8.9343	**8.93**
900	Fuel Cost $/hr	48892.9	48567.5	48360.9	**48353.4**
	Emission Kg/hr	701.428	694.172	693.791	**693.729**
	Loss MW	35.230	29.718	28.004	**28.004**

Table 10: Optimum results of 3-generating units

Power Demand MW	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)
500	33.2855	26.8885	89.9141	90.3852	135.7150	132.7453
900	92.3185	98.3707	150.1997	148.5549	220.4051	218.1615

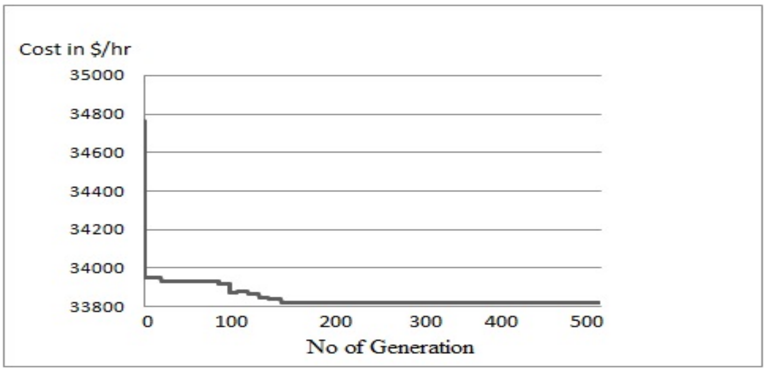

Figure 3: Convergence Curve of 6 Generating Unit

Conclusions

In this paper, a Differential Evolution (DE) algorithm has been proposed. DE has been successfully applied in order to obtain economic operation, minimal impact on environment and considering the transmission loss coefficient. Standard 3 and 6 generating units are considered to validate the performance of DE, which provides global optimum solution at fast convergence. DE method was compared with conventional method, RGA and SGA and Hybrid GA. The comparison shows that DE performs better then above mentioned methods. The DE has superior features, including quality of solution, stable convergence characteristics and good computational efficiency. Therefore, this results show that DE is proves to be promising technique for solving Economic Emission Dispatch (EED) problems in power system.

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