Emission Constraint Optimal Power Flow using Differential Evolution

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ABSTRACT
Objective of the power systems firm is to achieve the maximum profit and customer goodwill by providing reliable and quality power supply. This power system operation problem is solved by Optimal Power Flow (OPF). It gives requirement of operating states which satisfy the objective of the firm. Thermal power plants are the main source of power generation. Fuel cost of these power plants has to minimize for better profit at the same time it should satisfy system load demand, real, reactive power limit, voltage limit, power transmission limit and other limitations. For generation cost minimization Economic Load Dispatch (ELD) and Optimal Power Flow (OPF) was developed. When cost is the single objective, the power generation may pollute the environment. Thermal electric power could not be generated without pollution but this pollution can be reduced for the sake of good and healthy atmospheric condition. Differential Evolution (DE) algorithm is used in this paper to solve Emission Constraint Optimal Power Flow problem. Standard IEEE 30 bus, power system having 6 thermal power plants, is considered to validate the simulation.

Keywords
Deferential Evolution, Optimal Power Flow, emission dispatch, Newton Raphson power flow.

1. INTRODUCTION
Development of country and population growth needs more and more electric power at a reasonable price and pollution less power. But this electric power demand is supplied mainly by thermal power plants, which produce harmful gases like Sulfur Oxides SOx, Nitrogen Oxides NOx and Cox [1], [2]. General OPF solution aims on minimum generating cost and emission is not considered. Emission Constraint Optimal Power Flow problem aims to reduce emission level as well as generating or fuel cost. Environmental economic dispatch (EED) problem [3] was developed to find minimum generating cost and minimum emission, these problems are not consider the transformer tap position which is one of the main control variable in OPF [7], [12].

Rainer Storn R and Kenneth Price proposed novel heuristic algorithm called Differential Evolution (DE) in1997 [16], to fulfill the requirement the optimization technique. DE algorithm is intended for minimization problem which may non-differential, non-linear and multimodal. DE is Easy to implement and it has good convergence for global optimization. Suganthan P. N explains different mutation and crossover methods in DE [8].

Yong Wang, and Zixing Cai describes multi objective DE to constraint optimization problem [15]. DE is used to solve OPF [4], [10] but emission is not considered in the earlier literature. DE is also used to solve EED [5], [11] but important parameter of voltage magnitude and transformers are not considered.

Combined Economic Emission Dispatch (CEED) solved which consider only real power balance equality constraint [6]. Gnanadass R, and Narayana Prasad Padhy used Evolutionary Programming (EP) to solve CEED and a novel concept of modified price penalty factor [9] for better optimum solution. Like DE many heuristic algorithms like Artificial Bee Colony [13], Particle Swarm Optimization (PSO) [14], Genetic Algorithm [12], [18], etc.., are used to solve EED and OPF problems separately. This paper presents a problem which combines OPF and emission. To solve this control variables of Generators real power generation except slack bus, generator bus voltage magnitude and transformer tap position are considered. To calculate generation cost and emission quadratic cost function and emission function are considered in the paper.

2. DIFFERENTIAL EVOLUTION
The ability of DE is to optimize nonlinear, non-continuous and non-differential real world problems. Compare to other population based meta heuristic algorithms, DE emphasis on Mutation than Recombination or Crossover. It mutate vector with a help of randomly selected a pair of vector in the same population. The mutation guides the vector towards the global optimum. The distribution of the difference between randomly sampled vectors is determined by the distribution of these vectors. This enables DE function robustly and more as a generic global optimizer. DE works on population of vectors, where vector is a group of decision variables. Selection of decision variable is based on their impact on the problem to be optimized. These decision variables need to be encoded and set of initial values are chosen from the solution space. By mutation and recombination new vectors are created. The selection process selects the best vectors based on the selection criterion.

2.1 Encoding
Encoding is the process of converting group of decision variables into vector and objective function into fitness function. Ability of DE is to operate on floating point and mixed integer makes ease of encoding decision variables into vectors. Number of decision variables is the size of the vector and each vector gives one solution from the solution space for the problem defined

2.2 Mutation
The objective of mutation is to enable search diversity in the parameter space as well as to direct the existing vectors with suitable amount of parameter variation in a way that will lead to better results at a suitable time. It keeps the search robust and explores new areas in the search domain. There are 4 types of mutation [8].

DE/rand/1/ bin – Yi = Xr1+F*(Xr2 – Xr3)
DE/rand/2/bin – Yi = Xr1+F*(Xr2 – Xr3)+ F*(Xr4 – Xr5)
DE/best/1/bin – Yi = Xbest+F*(Xr1 – Xr2)
DE/best/2/ bin – Yi = Xbest+F*(Xr1 – Xr2)+ F*(Xr3 – Xr4)
r1≠ r2≠ r3≠ r4≠r5 are randomly selected

2.3 Crossover

Crossover aims at reinforcing prior successes by generating child individuals out of existing individuals or vectors parameters. The cross over constant is used to determine if the newly generated individual is to be recombined. There are two types of cross over namely Binomial and Exponential [8]. To form trail vector in binomial method a random number is generated, if this value is less than the cross over constant then mutated vector variable is considered otherwise target vector variable is considered.

2.4 Selection

Fitness of the trail vector and the target vector is compared and the vector which has minimum objective value is selected for the next generation. This keeps the population size constant for all the generation.

3. PROBLEM FORMULATION

Optimal Power Flow is a minimization problem, needs to minimize generation cost. In this work quadratic cost equation is considered as given below

$$C_t = \sum_{i=1}^{ng} \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \quad \text{\$/Hr} \tag{1}$$

Emission of harmful gases is calculated in ton/Hr using a quadratic equation as given below

$$E(P_G) = \sum_{i=1}^{ng} 10^{-2}(a_i + b_i P_{Gi} + c_i P_{Gi}^2) + d_i \exp(e_i P_{Gi}) \tag{2}$$

Emission constraint OPF is needs to minimize emission and generating cost. The *objective function* is

$$\text{Min } F(PG) = Ct + h*E(PG) \text{ \$/hour} \tag{3}$$

Where,
$F(P_G)$ = Emission constraint OPF objective function in \$/hour
Ct = Total generation cost in \$/hour
$E(P_G)$ = Total emission in ton/hour
α, β, γ = Cost coefficients of the generator
a, b, c, d, e = Emission coefficients of the generator
P_{Gi}, Q_{Gi} = Active and Reactive power of i^{th} generator
ng = Total number of generators
h = price penalty factor in \$/ton

Subject To:
Equality constraints

$$\sum_{i=1}^{ng} P_{Gi} = P_D + P_L \tag{4}$$

$$\sum_{i=1}^{ng} Q_{Gi} = Q_D + Q_L \tag{5}$$

Inequality constraints

$$V_{i(\min)} \le V_i \le V_{i(\max)} \quad \text{for i=1 to Nbus} \tag{6}$$

$$P_{Gi(\min)} \le P_{Gi} \le P_{Gi(\max)} \quad \text{for i=1 to ng} \tag{7}$$

$$Q_{Gi(\min)} \le Q_{Gi} \le Q_{Gi(\max)} \quad \text{for i=1 to ng} \tag{8}$$

$$t_{i(\min)} \le t_i \le t_{i(\max)} \quad \text{for i= 1 to Ntrans} \tag{9}$$

Where,
P_{Gi}, Q_{Gi} = Active and Reactive generation of i^{th} generator
P_D, Q_D = Active and Reactive demand
P_L, Q_L = Active and Reactive loss
V_i = Voltage at i^{th} bus
Nbus = Number of buses
ng = Number of generators
Ntrans = Number of transformers

4. DE APPROACH

Control variables are used to formulate a vector, in the specified problem real power generation of all generators except slack bus generator, voltage magnitude of all generators, transformer tap positions are considered. As test case IEEE 30 bus considered, which has 6 generators and 4 transformers gives 5 real power (except slack bus), 6 generator voltages and 4 transformers (total 15 variables) are considered as control variables. Population size or number of vectors considered is 66 for the simulation.

$$\text{Vector,} \quad Y = [X_1, X_2 \ldots X_{15}] \tag{10}$$

$$\text{Population, } P = [Y_1, Y_2 \ldots Y_{66}] \tag{11}$$

4.1 Initialization

Initialization is the process of generating vectors in a population within its minimum and maximum limits using the equation given below

$$Y^{(0)} = Y^{min} + \eta\,(Y^{max} - Y^{min}) \tag{12}$$

In the above equation Y^{min} and Y^{max} is minimum and maximum limit of decision variables, η is a random number between 0 and 1.

4.2 Mutation

Mutation is the main process in DE, weighted differences of randomly chosen vectors other than target vector is used to mutate the target vector. Target vector is a vector which is considered for the mutation. Mutation rule used in the work is given below

$$Y_i = Y_{best} + F*(Y_{r1} - Y_{r2}) + F*(Y_{r3} - Y_{r4}) \tag{13}$$

$$\text{and } r1 \ne r2 \ne r3 \ne r4 \ne best \tag{14}$$

In the equation (13), Y_i is the target vector; Y_{best} is the vector which gives minimum value among all the vectors in the current generation. Y_{r1}, Y_{r2}, Y_{r3} and Y_{r4} are randomly chosen vector in the population of current generation. F is scaling factor, which may have value between 0 and 1.

4.3 Crossover

Crossover is the process of generating trail vector from mutated and target vector. Trail vector is a combination of target and mutated vector. For each control variable in a vector a random number between 0 and 1 is generated if it is less than crossover constant chosen, then control variable from mutated vector is selected otherwise it is selected from target vector to form a trail vector as given below.

$$X_{trail}^{(G)} = \begin{cases} X_{mutate}^{(G)} \rightarrow if\,(\eta \le C_R) \\ X_{target}^{(G)} \ldots\ldots\, otherwise \end{cases} \tag{15}$$

In above equation X is a control variable, superscript G is the generation number, η is a random number between 0 and 1.

4.4 Selection

For the control variables in target vector and trail vector Newton Raphson power flow is executed to satisfy equality constraints (4) and (5), know the dependent variables value like load bus voltages, reactive power generation and to evaluate objective function given by equation (3). If the objective function value of trail vector is less than the target vector, then trail vector is consider to next generation otherwise target vector is considered to next generation.

$$Y_i^{(G+1)} = \begin{cases} Y_{trail\_i}^{(G)} \rightarrow if \ldots f(Y_{trail\_i}^{(G)}) \le f(Y_{target\_i}^{(G)}) \\ Y_{target\_i}^{(G)} \ldots\ldots\ldots\ldots\ldots otherwise \end{cases} \qquad (16)$$

for i= 1 to No. of population

In the above equation Y is a vector, superscript G represents generation number and f(Y) is the objective function value for the vector Y.

These processes mutation, crossover and selection are repeated for generation to generation till the stopping criterion.

5. SIMULATION RESULTS

This emission constraint OPF is implemented in MATLAB, R2010a – 32 bit version. Intel Core-2, CPU at 2.00 GHz processor is used for the installation and execution. Parameters of DE are considered as, number of decision variable (D) is 15, population size (NP) is 66, scaling factor value (F) 0.9 and crossover constant (CR) value 0.3.

Table 1, provide values of maximum and minimum generation of generators and cost coefficient. Table 2 gives emission coefficient for the system. Minimum and maximum limit for all bus voltages is taken as 0.95pu and 1.05pu. Minimum and maximum limits of transfer tap positions are 0.9pu and 1.1pu. Real and reactive power load for the system is 283.4 MW and 126.2 MVAR respectively. Price penalty factor is taken as 1000 $/ton.

Table 1. Generator Limits & Cost Coefficients

Gen No	Real Power Limit (MW)		Reactive Power Limit (Mvar)		Cost Coefficients		
	Min	*Max*	*Min*	*Max*	α	β	γ
1	5	50	-40	50	10	200	100
2	5	60	-40	50	10	150	120
3	5	100	-40	40	20	180	40
4	5	120	-10	40	10	100	60
5	5	100	-6	24	20	180	40
6	5	60	-6	24	10	150	100

Table 2. Generator Emission Coefficients

Gen. No	Emission Coefficients				
	a	b	c	d	e
1	4.091	-5.554	6.490	2e-4	2.857
2	2.543	-6.047	5.638	5e-4	3.333
3	4.258	-5.094	4.586	1e-6	8.000
4	5.426	-3.550	3.380	2e-3	2.000
5	4.258	-5.094	4.586	1e-6	8.000
6	6.131	-5.555	5.151	1e-5	6.667

Output of simulation is given in table 3. The result of proposed method is compared with earlier literature results. It is observed that proposed method fuel cost 612.02 $/Hr is less than other methods and emission 0.20545 is less than other methods except MODE [5] but in MODE method generating cost higher, so proposed method may provide better solution to emission constraint OPF.

Table 3. Comparison of Generation Cost and Emission

Real Power Gen. (MW)	SPEA [1]	MODE [5]	PSO [14]	Proposed Method
P_{G1}	29.96	25.2758	17.613	18.7185
P_{G2}	44.74	40.6968	28.188	38.785
P_{G3}	73.27	56.1153	54.079	54.0016
P_{G4}	72.84	66.9946	76.963	75.8716
P_{G5}	11.97	53.6240	65.019	55.4841
P_{G6}	53.64	43.6732	44.569	43.1681
Fuel Cost $/hr	629.394	617.9962	612.35	**612.02**
Emission ton/hr	0.21143	0.2009	0.20842	**0.20545**

Convergence curve of DE approach to emission constraint OPF is given in Fig 1. In the simulation 200 iterations is taken as stopping criterion, so convergence is given for 200 iterations. Solution is converged around 58th iteration shows generation cost is settle down to 612.02 $/Hr and corresponding emission level is freeze to 0.20545 ton/hr is also clear from the convergence curve.

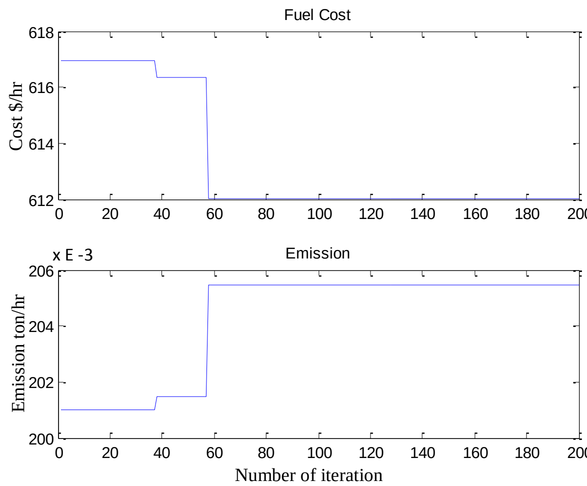

Fig 1: Convergence curve

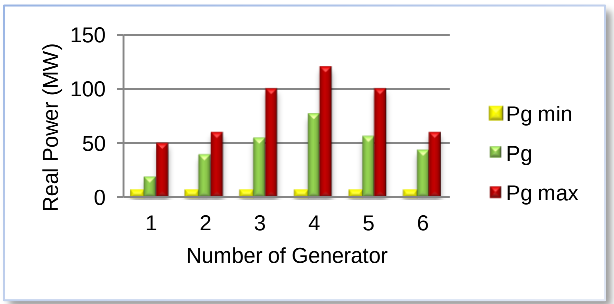

Fig 2: Real Power Generation

Fig 2, shows the real power generation of all 6 generators. These real power generation is substitute in objective function to get best generation cost and emission. It is clear from the fig 2 the generation is within its limits.

6. CONCLUSION

Optimal Power Flow (OPF) is a nonlinear nonconvex problem, conventional techniques like NR method is inferior to find best (global) optimal value. Meta heuristic techniques are superior in finding global optimal value. In this research paper one such meta heuristic technique, DE used to solve OPF. Prime importance of OPF is to reduce the generating cost, emission level and to satisfy all equality and inequality constraints. Equality constraint of power balance equation is satisfied, by NR method power flow used is a subset module in the algorithm. The results also guarantees control variables and dependent variables are within their limits. Test case IEEE 30 bus power system considered for demonstration. Results of proposed DE algorithm are compared with other popular algorithms in the literatures. From comparison it is clear the proposed DE algorithm provides the best solution for emission constraint OPF.

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