Hybrid Real coded Genetic Algorithm - Differential Evolution for Optimal Power Flow

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***Abstract*—Electric power providing companies has to deliver reliable electric power in quality and at minimum cost for the competition in deregulated environment. To know the power system security and operating state, power flows in lines and bus voltage magnitude and angle are calculated using power flow analysis, and to tune the power system for minimum operating cost while ensure security and reliability, Optimal Power Flow (OPF) is used. OPF is a non-convex, complex problem, conventional mathematical techniques gets struck in local optimal point based on the initial point. In recent years, heuristic algorithms are used to overcome local optimal solution and to reach global optimal solution. Heuristic algorithm Genetic Algorithm (GA) and Real coded GA (RGA) has better Selection and Cross-over operation, Differential Evolution (DE) has better Mutation process, inspires the hybrid of RGA – DE algorithm, presented in this paper. In this work RGA, DE and hybrid RGA – DE algorithms are used to find OPF solutions for a standard test IEEE 30 bus system.**

Keyword-Real coded Genetic Algorithm, Differential Evolution, Hybrid RGA-DE Algorithm, Optimal Power Flow, Newton Raphson power flow.

I. INTRODUCTION

Power system operation and planning needs the power flow analysis. A simple power flow analysis gives needed information but not an optimal. A simple economic load dispatch provides the optimal operating state of the power system but reactive, real power balance is not verified after the changes in generation pattern. The necessary of real and reactive power balance, economic operation and to limit physical and depended variables within limits, an Optimal Power Flow (OPF) is evolved. The main objective of the OPF is to find minimum operating cost without violating the limits and to be in the secure operating state. The classical mathematical programming methods to solve the OPF are Linear Programming (LP), Quadratic Programming (QP) and Non Linear Programming (NLP) method are inferior in finding global optimum and high sensitive to initial condition. Heuristic algorithms overcomes this local minimum values and finds global optimal values.

Alsac and Stott extend conventional Dommel-Tinney approach to find solution of OPF problem and used IEEE 30 bus system [4]. After their approach this IEEE 30 bus system becomes standard test case for most of the OPF problem solutions. Development and working of different heuristic algorithms like GA and DE are explained in references [1, 2]. Anastasios et al., [3] used Enhanced Genetic Algorithm which is a binary coded GA, for the enhancement number of bits is reduced to 25 bits. Preetha Pallavi and Vaithiyanathan [10] used real coded GA for their work and explain the working of RGA. References [7, 8, 9] used differential evolution technique to solve OPF, constraint combined economic emission dispatch problem and reactive power dispatch problem, provides necessary detail to formulate this hybrid heuristic technique. Niknam et al., [6] used a new heuristic technique, Honey Bee Mating algorithm to solve static and dynamic OPF. This paper also compares results of various heuristic algorithms. Sivasubramani and Swarup [5] used hybrid conventional Sequential quadratic programming with DE to find OPF solutions. In this work a new approach of hybrid two heuristic algorithms (RGA-DE) are carried out. To evolute the results standard IEEE 30 bus [4, 6] is considered and compared with previous results published in reference [6].

II. REAL CODED GENETIC ALGORITHM

John Holland introduced Genetic Algorithm (GA) in the year 1970s [1]. It mimics the Darwin's evolution theory and GA uses the concept of survival of fitness. GA is most popular optimization algorithm for solving nonlinear, non-convex optimization problem [2]. GA needs to find global optimal solution in the constraint solution space. Based on the chromosome used GA is classified as binary coded GA [3], real coded GA. In real coded GA (RGA) all variables are real numbers as in real world application. In RGA objective function is taken as fitness function, control variables are taken as genes and group of control variables are considered as chromosome [10]. Control and depended variables' minimum and maximum limit forms the boundary of the solution space. RGA explores this space and finds the global best value. As like nature it optimizes the chromosome fitness through generation by generation RGA and tunes the genes (control variables) to the best optimal value. A set of chromosome is called population. RGA evaluate each chromosome in the population to keeps better chromosome and replace unfit chromosome in each generation, finally it brings the best chromosome which has global optimum value. The general procedure for RGA is given as 1) Defining fitness function, 2) Initialize population, 3) Evaluate the fitness of all the individual in the population, 4) create new population by performing crossover and mutation, 5) Evaluate the new population until stooping criteria. The three main operation of GA is selection, Cross Over, and Mutation.

A. Selection

Selection is the process of scrutinizing high fitness chromosome in the current population and provides opportunity in succeeding generation. The different types of selection schemes [1, 2] are Tournament selection, Truncation selection, Linear Ranking selection, Elitist selection and Roulette Wheel selection.

B. Crossover

Crossover is the process of interchanging information (genes) among the parents in the mating pool. The crossover can be classified as single point, tow point and multi point crossover. In single point crossover after specified point the genes of the two parents are interchanged. In two point crossover the genes in between two specified point are interchanged.

C. Mutation

Mutation is the process of toggle the specified bit of a gene in the chromosome for binary coded GA. In real coded GA particular gene value is modified without violating its' limits. Mutation is required for divergent search in the solution space. The probability of mutation in RGA is very less as compared to crossover.

D. Stopping criteria

Evolution of generation is stopped by either maximum number of generation or solution convergence. If there is an improvement of solution in every generation then convergence criteria may implement, else if negligible improvement is evidenced then maximum generation might be the best choice

III. DIFFERENTIAL EVOLUTION

Differential Evolution was first proposed over1994-1996 by Storn and Price at Berkely [2]. The ability of DE is to optimize nonlinear, non-continuous and non-differential real world problems. Compare to other population based heuristic algorithms, DE emphasis on Mutation than Crossover. Real valued control variables are grouped and form a vector, group of vectors are called population. For mutation it uses randomly selected vectors in the same population. This mutation helps the vector to move towards the global optimum [7, 8, 9]. The process mutation and crossover produce new vectors and selection process selects the best vectors based on the selection criterion.

A. Mutation

The objective of mutation is to enable search diversity in the solution space and to direct the vector to approach global optimal solution. Commonly used four types of mutation are DE/rand/1, DE/rand/2, DE/best/1and DE/best/2. For this mutation process two to five vectors apart from target vector is chosen, for last two type of mutation rule best vector in the current population is used.

B. Crossover

Crossover aims at reinforcing prior successes to current population. Binomial or Exponential technique is used for this crossover. In binomial approach, a cross over constant is used to determine the importance of control variable in mutated or target vector. Outcome of the crossover process is trail vector.

C. Selection

Selection is the process of selecting either a target vector or trail vector based on their objective value.

D. Stopping criteria

Maximum number of iteration is commonly used stopping criteria. Convergence criteria may used if last few iteration doesn't have any improvement.

IV. HYBRID RGA-DE

Hybrid GA–DE algorithm uses advantage of GA and DE to find global optimal value. In this algorithm GA selection, crossover is chosen and mutation is chosen from DE, maximum generation is considered as stopping criteria. This fusion of algorithms provides best solution as compared to individual algorithms.

A. Initialization

Random initial values of all control variables are chosen within its minimum and maximum limits, is the first step to start the hybrid algorithm.

B. Selection

Selection is the process of choosing high fitness chromosome to the mating pool. In this hybrid algorithm versatile Roulette Wheel selection is used.

C. Crossover

Crossover is the process of sharing vital information among the fittest chromosomes in the mating pool. Single point crossover is used in this hybrid algorithm.

D. Mutation

To improve mutation process, ‘DE/rand/1’ mutation rule is used. Mutation is carried out for all chromosomes in the population. A selected chromosome for mutation is called target vector, apart from target vector three more distinct chromosomes are selected to perform mutation.

E. Stopping criteria

Execution of selection, crossover and mutation operation for a population is called one generation. This heuristic algorithm is an iterative algorithm and repeats this process again and again till the stopping criteria. In hybrid algorithm these iterations are called generations and Maximum number of generation is used as stopping criteria.

V. OPF PROBLEM FORMULATION

Optimal Power Flow problem is a minimization problem which is stated as follows. The objective is to minimize the generation cost as given in equation (1). This solution has to balance the real and reactive power flow as given in equation (2) and (3), which from a equality constraint to the problem. Control variable of this problem are generator real power (excluding slack bus), generator bus voltage magnitude and transformer tap settings should be within their lower and upper limits as given in equations (4), (5) and (7). Dependent variables, load bus voltage magnitudes and generator reactive power generations should also be within their lower and upper limits as given in equation (4) and (6).

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

Subject To:

Equality constraints

$$\sum_{i=1}^{ng} P_{Gi} = P_D + P_L \tag{2}$$

$$\sum_{i=1}^{ng} Q_{Gi} = Q_D + Q_L \tag{3}$$

Inequality constraints

$$V_{i(\min)} \le V_i \le V_{i(\max)} \text{ for i=1 to Nbus} \tag{4}$$

$$P_{Gi(\min)} \le P_{Gi} \le P_{Gi(\max)} \text{ for i=1 to ng} \tag{5}$$

$$Q_{Gi(\min)} \le Q_{Gi} \le Q_{Gi(\max)} \text{ for i=1 to ng} \tag{6}$$

$$t_{i(\min)} \le t_i \le t_{i(\max)} \quad \text{ for i=1 to Ntrans} \tag{7}$$

Where,

C_t = Total generation cost in $/hour

α, β, γ = Cost coefficients of the generator

P_{Gi}, Q_{Gi} = Active and Reactive power 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

$V_{min,} V_{max}$ = Minimum and Max limits of Voltage

$P_{Gmin,}$ P_{Gmax} = Min and Max limits of real power

$Q_{Gmin,}$ Q_{Gmax} = Min and Max limits of reactive power

t_{min}, t_{max} = Min and Max limits of transformer tap position

Nbus = Number of buses

ng = Number of generators

VI. SOLVING OPF USING RGA

A. Initialization

This RGA is used to solve OPF for standard test case IEEE 30 bus system, which has 6 generators including slack bus generator, 4 transformers and 41 transmission line [4, 6]. Generator bus (excluding slack bus) real power, all generator bus voltage magnitude and transformer tap position are considered as control variables. Hence 15 control variables constitute of 5 real power generations, 6 generators voltage magnitude and 4 transformers tap. These control variables are named as genes and it should be within their limits. Group of these 15 genes are called chromosome (Y) as given in equation (9), group of these chromosomes forms a population as given in equation (8), in this work 80 chromosomes are considered. Maximum number of generation is taken as 200 generation. Initial values of these genes are chosen randomly using a random number generated by MATLAB software as per the equation (10).

$$Pop = [Y_1, \; Y_{2,} \quad \ldots \quad Y_{np}] \tag{8}$$

$$Y = [Gene_1, Gene_2, \; \ldots \; Gene_{15}] \tag{9}$$

$$Gene = Gene_{min} + \eta.(Gene_{max} - Gene_{min}) \tag{10}$$

Where,

Pop - Population

Y - Chromosome

np – Population size

$Gene_{max}$, $Gene_{min}$ - Gene maximum and minimum limit

η - Random number within [0 1]

B. Selection

Roulette wheel selection which is based on cumulating probability, is used to find fittest chromosome for the mating pool. Cumulative probability of all 80 chromosomes is calculated and roulette wheel is rotated 80 times to get fittest 80 chromosomes from the population.

C. Crossover

Single point crossover is used in this work, which interchanges a set of genes from one chromosome to another after a crossover point. In this process 80 random numbers are generated corresponding to each chromosome. If generated random number for the chromosome is less than the crossover constant (0.25) then the chromosome is selected to mating pool for crossover operation. Once the mating pool is formed a random number within a number of genes is generated, this number is taken as crossover point, now two chromosomes are taken from the mating pool then interchange of genes in the crossover point is carried out.

D. Mutation

Mutation is the process of changing a gene value in the chromosome based on the probability of mutation constant (0.01). A random number corresponding for each gene is generated; if this number is less the mutation constant then the gene is mutated. In this RGA after the mutation, gene values are confirmed to their limits.

VII. SOLVING OPF USING DE

A. Initialization

As like GA, 15 control variables constitute of 5 real power generations, 6 generators voltage magnitude and 4 transformers tap settings are considered [7, 8]. These set of control variables are named vectors. Group of these vectors forms a population, in this work 80 vectors are considered. Random initial value of 15 control variables is chosen from the solution space bounded by its minimum and maximum limits. This forms a vector Y as given in equation (11). 80 such vectors form a population as given in equation (12).

$$Y = [X_1, \quad \ldots \quad X_{15}] \tag{11}$$

$$Pop = [Y_1^{(G)}, \; \ldots \; Y_{np}^{(G)}] \tag{12}$$

B. Mutation

Mutation is the process of changing one or more parameters of an existing vector. In this approach DE/rand/1 rule is used, and it is achieved by adding the weighted difference of two randomly selected vectors as given in equation (13).

$$Y^{1(G)} = Y_a^{(G)} + SF\,(Y_b^{(G)} - Y_c^{(G)}) \tag{13}$$

Where

Y_a, Y_b, Y_c = randomly chosen vectors, from the population

$a \neq b \neq c$

C. Crossover

Target vector $Y^{(G)}$ and mutated vector $Y^{1(G)}$ are used to get trail vector $Y^{11(G)}$ based on binomial condition as given below, For this a cross over constant C_R (0.25) is used to determine the selection of decision variable among mutated or target vector. If the generated random number for the corresponding decision variable is less than C_R then a decision variable is taken from mutated vector otherwise a target vector decision variable is chosen to form a trail vector as given in equation (14)

$$Y^{11(G)} = \begin{cases} Y^{1(G)} \rightarrow if - \eta \ \leq C_R \\ Y^{(G)} \text{..........} otherwise \end{cases} \tag{14}$$

D. Selection

Selection is the process of choosing either a target or trail vector based on their fitness. Fitness function for target and trail vector is calculated the best fitness vector is chosen among these vectors as given in equation (15).

$$Y^{(G+1)} = \begin{cases} Y^{11(G)} \rightarrow if \ldots f\,(Y_i^{11(G)}) \leq f\,(Y_i^{(G)}) \\ Y^{(G)} \text{..........................} otherwise \end{cases} \tag{15}$$

Where

$Y^{(G)}, Y^{1(G)}, Y^{11(G)}$= target, mutated and trial vector

SF = Scaling factor

C_R = Crossover constant

np – Population size

$Gene_{max}$, $Gene_{min}$ - Gene maximum and minimum limit

η - Random number within [0 1]

X = control variable or gene

VIII. SOLVING OPF USING HYBRID RGA-DE

A. Initialization

As like RGA initial values of all genes are chosen within its minimum and maximum limits as given in table I. In this approach a population has 80 chromosomes, each chromosome has 15 genes, are initialised as given in equations (8) to (10).

B. Selection

As like RGA roulette wheel selection is used to select fittest chromosomes for the mating pool. Cumulative probability of all chromosomes is calculated and then a random number corresponding to each chromosome is generated if this random number of the chromosome is less than the crossover constant 0.25, then chromosome is chosen for mating.

C. Crossover

As like RGA single point crossover is carried out in this approach. Two parents chromosome from the mating pool is chosen and a random number for the crossover operation is generated, which gives the crossover point. At the crossover point the genes of the parent chromosomes are interchanged

D. Mutation

As like DE mutation rule, ‘DE/rand/1’ is used for mutation process. Mutation is carried out for all chromosomes in the population. A selected chromosome for mutation is called target vector, apart from target vector three more distinct chromosomes are selected to perform mutation. Mutation is carried out as given in equation (13). For this mutation scaling factor SF is taken as 0.7.

E. Stopping criteria

In this approach iteration based stopping criteria is used. Maximum number of generation is taken as 200. Hence the process of selection, crossover and mutation is repeated for generation by generation till the generation count reaches 200.

IX. TEST RESULTS

IEEE30 bus is considered to evaluate the performance of developed algorithms. OPF solution of RGA, DE and hybrid RGA-DE are compared in this section. Table I, gives the fuel cost coefficient, minimum and maximum real power generation limit of the 6 generators.

TABLE I
Generator Details

Gen. No	Real Power Generation Limit (MW)		Cost Coefficients		
	Min	Max	α ($)	β ($/MWh)	γ ($/MWh^2)
1	50	200	0	2.00	0.00375
2	20	80	0	1.75	0.01750
3	15	50	0	1.00	0.06250
4	10	35	0	3.25	0.00834
5	10	30	0	3.00	0.02500
6	12	40	0	3.00	0.02500

Control or decision variables for this system are generator real power generation (excluding slack generator), generator bus voltage magnitude, transformer tap positions, and dependent variables are load bus voltage magnitudes. Table I give the limits of real power generation and other control and depended variables limits are given in Table II.

TABLE III
Limits on Variables

Type of Variable	Description	Min. Value (PU)	Max. Value (PU)
Control	Transformer Tap Position	0.90	1.10
Control	PV bus Voltage	0.95	1.10
Dependent	PQ bus Voltage	0.95	1.05

A. Result of RGA

RGA uses 80 chromosomes, each chromosome has 15 genes. The lowest cost generations by the chromosomes are selected using roulette wheel selection, then crossover and mutation operations are carried to get better chromosome for the next generation. The generation is stopped after 200th iteration and convergence curve is shown in figure 1. Cost of generation is 805.453 $/hr.

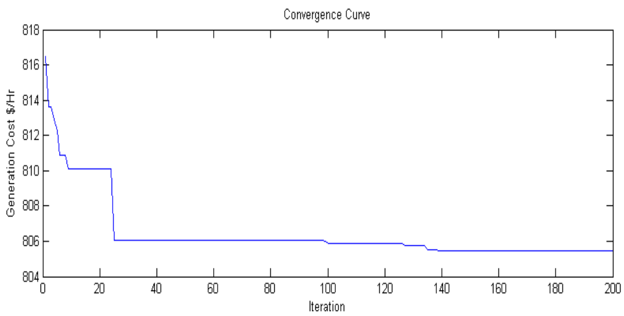

Fig. 1. Convergence Curve of RGA

Real power generation of all 6 generators is shown in Figure 2. Blue (first) bar shows the minimum limit, Green (second) bar shows actual generation of each generator and Red (third) bar shows maximum limit of the generators. Slack bus generates maximum power 176.103 mega watt (MW) and 5th generator in the system generates minimum power of 10.482 MW. This bar chart also guarantees that the generation is within the limits specified in table I

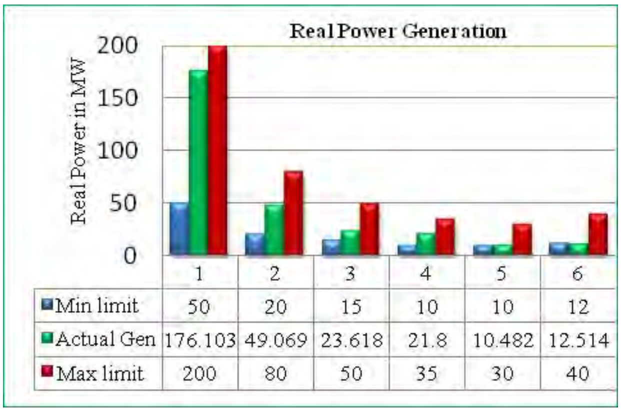

Fig. 2. Real Power generation with respect to its limits-RGA

B. Result of DE

DE uses 80 vector, each vector has 15 control variables. 200 iterations are performed to get global optimal solution. Convergence curve for DE is shown in figure 3. It is evident from the convergence curve DE has better convergence than GA. The cost of generation in DE algorithm is 804.169 $/hr.

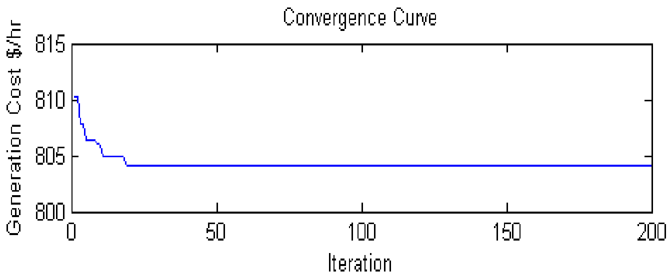

Fig. 3. Convergence Curve of DE

Real power generations are shown in Figure 4. Blue (first) bar shows the minimum limit, Green (second) bar shows actual generation of each generator and Red (third) bar shows maximum limit of the generators. Slack bus generates maximum power 186.942 MW and 5th generator in the system generates minimum power of 10.551 MW.

Fig. 4. Real Power generation with respect to its limits-DE

C. Result of hybrid RGA-DE

In hybrid GA - DE algorithm 80 chromosomes are considered and 200 generation is taken as stopping condition. In this Hybrid algorithm Initialization, Selection and Cross Over operations are performed as RGA and Mutation is done as like DE. This algorithm provides better result as compared to other two algorithms. Convergence curve of hybrid GA - DE is shown in figure 5.

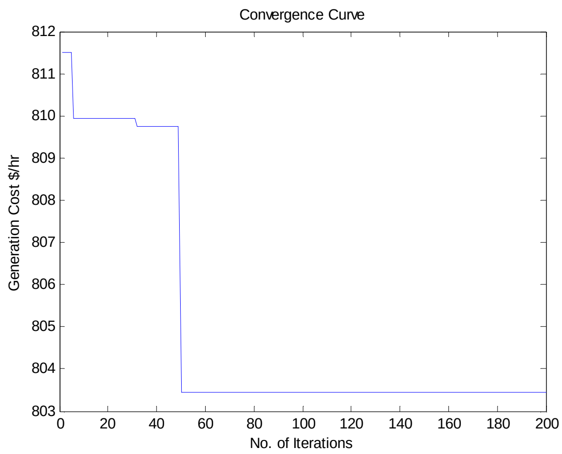

Fig. 5. Convergence Curve of RGA-DE

Real power generations are shown in Figure 6. Slack bus generates maximum power 174.993 MW and 6th generator in the system generates minimum power of 12.104 MW.

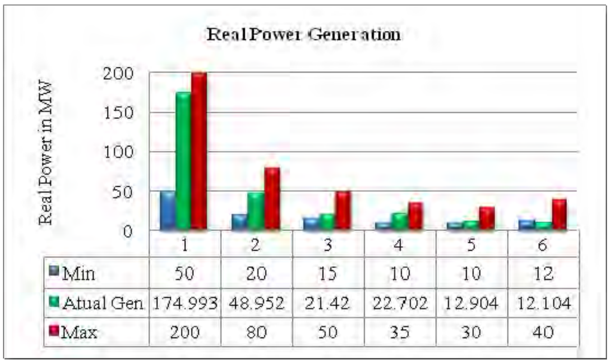

Fig. 6. Real Power generation with respect to its limits for hybrid RGA-DE

D. Comparison of Algorithms

Results of OPF for the IEEE 30 bus is obtained from RGA, DE and hybrid RGA-DE is compared and given in the Table III. All these three algorithms used 15 control variables, 80 number of chromosome and maximum iteration is limited 200. Minimum generating cost obtained from RGA is 805.453 $/hr, DE is 804.169 $/hr and hybrid GA&DE is 803.446 &/hr. Among these algorithms hybrid GA-DE provides lowest generating cost for the same system. Power generation of RGA, DE and HGA&DE algorithms are shown in the figure 7.

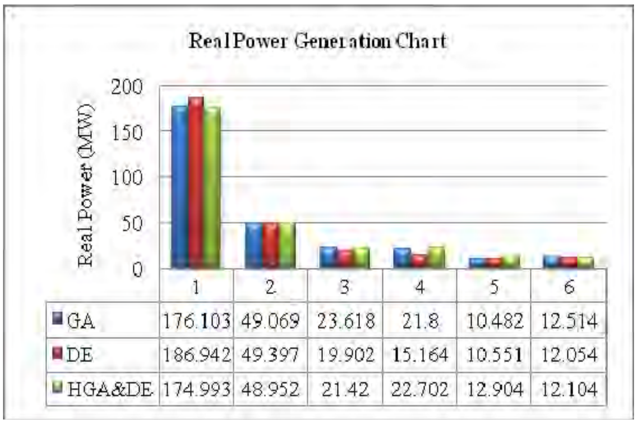

Fig. 7. Comparision of Real Power generaion

Table III shows comparative result of OPF solutions, for GA and Simulated Annealing (SA) results are referred [6] from the literature with the implemented RGA, DE and hybrid RGA-DE. From the comparison generation cost of hybrid RGA-DE is lowest.

TABLE IIIII
Comparison of Algorithms

Gen. (MW)	GA [6]	RGA	SA [6]	DE	HGA& DE
PG1	170.1	176.103	192.51	186.942	174.993
PG2	53.9	49.069	48.395	49.397	48.952
PG3	20.6	23.618	19.55	19.902	21.42
PG4	18.8	21.8	11.62	15.164	22.702
PG5	12	10.482	10	10.551	12.904
PG6	17.7	12.514	12	12.054	12.104
Gen. Cost $/hr	805.94	805.453	804.107	804.169	**803.446**

X. CONCLUSION

This paper discussed real coded GA (RGA), DE and hybrid GA-DE for solving OPF. Results of various algorithms are compared and it is evident hybrid GA-DE provides lowest generating cost. For calculation of generating cost all algorithms used same set of control variables, population size and iterations. These algorithms are confirmed the minimum and maximum limits on physical and control variables. Equality constraints of real and reactive power balance are satisfied by executing Newton Raphson power flow.

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