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Application of EP to Multiple Fuel Options Economic Dispatch

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ABSTRACT: This paper presents the Accelerated Evolutionary Programming (AEP) to solve economic dispatch with valve point effects and multiple fuel options. Also this paper is aimed to explore the comparison of performance of the different evolutionary programming (EP) techniques. The six EP techniques considered for comparison are: 1.Classical Evolutionary Programming (CEP), 2.Fast Evolutionary Programming (FEP), 3.Mean Fast Evolutionary Programming (MFEP), 4.Improved Fast Evolutionary Programming (IFEP), 5.Modified Evolutionary Programming (MEP) and 6.Accelerated Evolutionary Programming (AEP). Two bench mark problems are considered to show the relative performance of the different EP techniques. First test problem considers multiple fuel options alone and the next problem addresses both valve-point effects and multi-fuel options. AEP is compared with the results of (i) Conventional Genetic Algorithm with multiplier updating (CGA_MU) and (ii) Improved Genetic Algorithm with multiplier updating (IGA_MU) methods for the same bench mark problems. The results show that the AEP gives the minimum generation cost than any other methods.

KEYWORDS: Economic Dispatch, Valve point effects, Multiple fuel options, Accelerated Evolutionary Programming

1. INTRODUCTION

The economic dispatch problem is one of the important optimization tasks in power system operation for allocating generation among the committed units such that the constraints imposed are satisfied. Improvements in scheduling the unit outputs can lead to significant cost savings. Traditionally, in the economic dispatch problem, the cost function for each generator has been approximately represented by a single quadratic function, and the valve-point effects were ignored. This would often introduce inaccuracy in the resulting dispatch. Since the cost curve of a generator is highly nonlinear, containing discontinuities, the cost function is more realistically denoted as a segmented piecewise nonlinear function [1,2] rather than a single quadratic function. Additionally, the generating units supplied with multi-fuel sources (coal, nature gas, or oil) have the problem of selection of the most economic fuel to burn.

In literature, the economic dispatch problems with valve-point and multi-fuel effects are represented as a non-smooth optimization problem with equality and inequality constraints. In [3] dynamic programming (DP), [9] Tabu search, [4] genetic algorithm (GA), [5, 11] evolutionary programming (EP), [10] hybrid EP combined with sequential quadratic programming (EP-SQP), and [12] particle swarm optimization technique with the SQP method (PSO-SQP) consider only valve-point effects in the economic dispatch problem.

In 1 hierarchical method (HM), [3] Hopfield neural network approach (HNN), [6] adaptive Hopfield neural network method (AHNN) and [8] EP have considered only the multi fuel options. Recently, Jong-Bae Park [14,15] solves economic dispatch with valve-point loadings and multi-fuel effects separately using modified PSO (MPSO) and Improved PSO (IPSO). However, none of the studies mentioned above, consider both the valve-point loadings and multi-fuel options. To obtain an accurate and practical economic dispatch solution, the realistic operation of the economic dispatch problem should be taken both valve-point effects and multiple fuel options into account. Chao-Lung Chiang [13] solved this problem using improved genetic algorithm with multiplier updating (IGA_MU) technique.

Yao *et al.* [17] a Cauchy-mutation-based EP, called fast EP (FEP), which demonstrated much better performance than CEP in converging to a near-global optimum point on some benchmark mathematical functions. Chellapilla and Fogel [18] a fast EP using the weighted mean of Gaussian and Cauchy mutations, called henceforth MFEP, with an objective of having a step size greater than Gaussian mutation and smaller than Cauchy mutation so that advantages of both Gaussian as well as Cauchy mutations can be exploited. Yao *et al.* [19] an improved FEP (IFEP) that uses both Gaussian and Cauchy mutations to create offspring from the same parent and better ones are chosen for next generation. The performances of FEP, MFEP, and IFEP have been tested on economic dispatch problems with valve point effects by Nidul Sinha *et al.* [20]. P.Venkatesh *et al.* [21] an EP approach using non linear scaling factor to improve the convergence performance. Jong-Hwan Kim *et al.* [16] and Ping Wang *et al.* [23] solved control system problems using Accelerated Evolutionary Programming (AEP).
In this paper, the following EP techniques are applied to economic dispatch problem with valve-point effects and multiple fuel options:

i) CEP with Gaussian mutation

ii) FEP with Cauchy mutation

iii) MFEP with mean of Gaussian and Cauchy mutations

iv) IFEP with better of Gaussian and Cauchy mutations

v) MEP with step size scaling factor

vi) Accelerated Evolutionary Programming (AEP)

The above EP techniques are applied to the economic dispatch problems and compared using two bench mark problems. The first bench mark problem considers 10-generators system with multiple fuel options. The second test problem addresses both valve-point effects and multiple fuel options. The performances of CEP, FEP, MFEP, IFEP MEP and AEP are compared. The results are compared with the results of Conventional Genetic Algorithm with Multiplier Updating technique (CGA_MU) and Improved Genetic Algorithm with Multiplier Updating technique (IGA_MU). Comparative results indicate that the AEP is more effective than the other methods.

II. FORMULATION OF ECONOMIC DISPATCH PROBLEM

2.1. Economic Dispatch with Smooth Cost Functions:

The economic dispatch problem is to find the optimal combination of power generations that minimizes the total generation cost while satisfying an equality constraint and inequality constraints. The most simplified cost function of each generator can be represented as a quadratic function:

$$\text{Minimize } C = \sum_{j=1}^{n} C(P_j) \qquad (1)$$

$$C(P_j) = a_j P_j^2 + b_j P_j + c_j \qquad (2)$$

n

(1)

(i)Power Balance Constraint:

The power balance constraints of the system and the subsystem, which consists of group of units belonging to same area, are given by,

$$\sum_{j=1}^{n} P_j - P_D = 0 \tag{3}$$

(ii)Operation Unit Constraint:

The MW output of an on-line unit must be allocated within the range bounded by its lower and upper limits of real power generation.

$$P_j(\min) \le P_j \le P_j(\max) \qquad j = 1,2,3 \tag{4}$$

2.2. Economic Dispatch Problem with Non-smooth Cost Functions

1) Non-smooth Cost Functions With Valve Point Effects: The generator cost function is obtained from a data point taken during "heat run" tests, when input and output data are measured as the unit slowly varies through its operating region. Wire drawing effects, which occur as each steam admission valve in a turbine starts to open, produce a rippling effect on the unit curve. To consider the accurate cost curve of each generating unit, the valve-point effects must be included in the cost model. Therefore, the sinusoidal function is incorporated into the quadratic function [4]. Typically, the valve point results in. as each steam valve starts to open, the ripples like in Fig.1. The cost function addressing valve-point loadings of generating units is accurately represented as [4], [11].

$$C_j(P_j) = a_j P_j^2 + b_j P_j + c_j + |e_j \times \sin(f_j \times (P_{j\min} - P_j))| \quad \text{\$/MW} \tag{5}$$

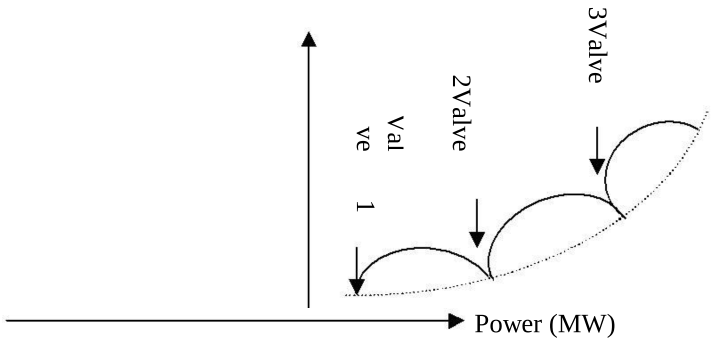

Fig.1. Cost Function with Valves

2) **Non-smooth Cost Functions with Multiple fuel options:**

The main objective of "Economic Dispatch with multiple fuel option" is to find which fuel is most economical to burn. Say, for example, a plant consisting of many generating units, which are supplied with numerous (Coal, Nature gas and Oil) of fuel may be faced with the dilemma of determining which fuel is most economical to burn. The piecewise quadratic function is used to represent multiple fuel options and the cost and incremental cost functions are illustrated in Fig.2. The hybrid cost function with the inequality constraints are given by,

$$C_{ij}(P_{ij}) = a_{ijk} P_{ij}^2 + b_{ijk} P_{ij} + c_{ijk} \quad ;k = F_1 \quad \text{if } P_{ij(\min)} \le P_{ij} \le P_{L1j}$$
$$= a P^2 + b P + c \quad ;k = F \quad \text{if } P < P \le P \tag{6}$$

$$= a_{ijk} P_{ij}^2 + b_{ijk} P_{ij} + c_{ijk} \quad ; k = F_3 \qquad \text{if } P_{L2j} < P_{ij} \le P_{ij(\max)}$$

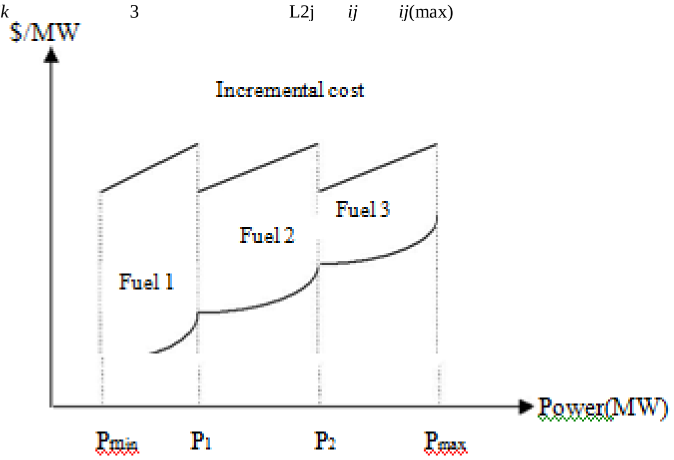

Fig.2. Piecewise quadratic and incremental cost functions of a generator

3) Non-smooth Cost Functions With both Valve Point Effects and Multiple fuel options:

To obtain an accurate and practical economic dispatch solution, the realistic operation of the economic dispatch problem should be considered both valve-point effects and multiple fuel options. This paper incorporated cost model, which combines the valve-point loadings and the fuel changes into one frame. Therefore, the cost function should combine (5) with (6), and can be realistically represented as,

$$\begin{aligned} C(P_j) &= a_{ijk} P_{ij}^2 + b_{ijk} P_{ij} + c_{ijk} + |e_{ijk} \times \sin(f_{ijk} \times (P_{j2\min} - P_{ij}))| \; ; k = F_1 \quad \text{if } P_{ij(\min)} \le P_{ij}^1 \le P_{L1j} \\ &= a_{ijk} P_{ij}^2 + b_{ijk} P_{ij} + c_{ijk} + |e_{ijk} \times \sin(f_{ijk} \times (P_{j2\min} - P_{ij}))| \; ; k = F_2 \quad \text{if } P_{L1j} < P_{ij}^2 \le P_{L2j} \\ &= a_{ijk} P_{ij}^2 + b_{ijk} P_{ij} + c_{ijk} + |e_{ijk} \times \sin(f_{ijk} \times (P_{j2\min} - P_{ij}))| \; ; k = F_3 \quad \text{if } P_{L2j} < P_{ij}^3 \le P_{ij(\max)} \end{aligned} \tag{7}$$

III. APPLICATION OF EP TO MULTIPLE FUEL OPTIONS ECONOMIC DISPATCH

1) Representation of solution:

In economic dispatch with multiple fuel options, the solution needs to represent both economic dispatch and fuel selection.

2) Initialization:

The initial population of parent individuals P_{ij} for i = 1,2,.....m is selected randomly from a feasible range for each independent unit j. Typically the distribution of initial trial is uniform. Only economic dispatch vector (P) is found randomly and the fuel selection vector(f) is then determined by using the components of economic dispatch vector (P_{ij}).

3) Creation of Off Spring:

A new offspring population of the solution is produced from the existing parent population by mutating each individual. Let P_{ij}' be generation of j^{th} unit of the i^{th} individual in off-spring.

The new power generation P_{ij}' is formed from the old generation P_{ij} by adding it with a Gaussian random number N as

$$P_{ij}' = P_{ij} + N(0, \sigma_{ij}^{2}) \tag{8}$$

The Gaussian random numbers have a mean of zero and a standard deviation of •ij^2 (Mutation Factor). The expression designed for □$_{ij}$ is,

$$\sigma_{ij} = \beta(P_{j\max} - P_{j\min}) C_j / C_{\min} \tag{9}$$

The objective function is,

$$Minimize\ C = \sum_{j \square 1}^{n} C_j(P_{ij}) + \gamma(P_{dc} - P_d')^2 \tag{10}$$

where, γ = penalty co-efficient whose value is large

The initial population and their offspring created by mutation form a combined population of 2m individuals.

4) Competition and Selection:

The parent trial vector P_j and the corresponding off-spring P_j' compete for survival with each other within the competing pool and the selection is done by comparing the objective function of parent vectors with the corresponding objective function of off-spring vectors in the population. The best vectors having minimum cost, whether parent vector P_j or offspring vector P_j' are selected as new parents for the next generation.

5) Stopping Rule:

During initialization, the maximum number of generations is fixed and it is checked for convergence. If the convergence condition is not met the Mutation and Competition processes will run again.

IV. DIFFERENT EP METHODS TO SOLVE ED PROBLEM

(i) Classical Evolutionary Programming (CEP):

In this method, an offspring vector P'_{ij} is created from each parent by adding to each component of P_{ij} ,a Gaussian random variable with a zero mean and a standard deviation proportional to the scaled cost values of the parent trial solution, i.e.,
where *N(0,* □ $_{ij}^{2}$ *)* represents a Gaussian random variable with mean 0 and standard deviation

$$P_{ij}' = P_{ij} + N(0, \sigma_{ij}^{2}) \qquad \text{for } j = 1,2,\ldots.n \tag{11}$$

(ii) Fast Evolutionary Programming (FEP):

In this method, an offspring is created by

$$P'_{ij} = P_{ij} + \sigma_{ij} .C_{ij}(0,1) , \qquad \text{for } j = 1,2,\ldots.n \tag{12}$$

where C_{ij} (0,1) is a Cauchy random variable with scale parameter t = 1 centered at zero that is

generated anew for each value of j.

(iii)Combined Gaussian and Cauchy mutations (MFEP):

In this method, an offspring is created as

$$P'_{ij} = P_{ij} + (\sigma_{ij} / 2)\left\{N_{ij}(0,1) + C_{ij}(0,1)\right\} \tag{13}$$

where N_{ij} (0,1) and C_{ij} (0,1) are Gaussian and Cauchy random variables, respectively, to be

generated anew for each value of j .

(iv)Improved Fast Evolutionary Programming (IFEP):

$$P'_{1ij} = P_{ij} + \sigma_{ij} .N_{ij}(0,1)$$

$$P_{2ij} = P_{ij} + \sigma_{ij} .C_{ij}(0,1) \tag{14}$$

Using the method of choosing the better from two offspring generated from each parent, one by Gaussian mutation and the other by Cauchy mutation (in IFEP). Let P'_{1ij} and P'_{2ij} be the two offspring generated from the parent P_{ij} The values of the objective function value of both offspring are evaluated, compared and better individuals are chosen as parents for next generation.

(v) Modified Evolutionary Programming (MEP):

This modified EP (MEP) method is different from above four methods [21]. In this method, step and nonlinear scaling factor are used to obtain the best solution. The decrement step (g) for step size scaling factor is evaluated as follows:

$$g = \frac{\bullet_{max} - \bullet_{min}}{N\,m(k)} \tag{15}$$

where $N\,m(k)$ is the maximum number of generations.

In this paper, nonlinear scaling factor is used. For the first 30% of total number of generations $N_1(k)$, the decrement (g_1)of the scaling factor is computed as follows:

$$g_1 = \frac{\bullet_{\max} - \bullet_{mid}}{N_1(k)} \tag{16}$$

where $\bullet_{mid}$ is the midpoint of scaling factor range.

For the remaining 70% of the total number of generations $N_2(k)$, the decrement (g_2) of the scaling factor is given by

$$g_2 = \frac{\bullet_{mid} - \bullet_{\max}}{N_2(k)} \tag{17}$$

(vi) Accelerated Evolutionary Programming (AEP):

AEP is based on EP is developed for the improvement of the convergence speed without decreasing the diversity among the individuals. AEP uses two variation operators according to the evaluation conditions. One is a direction operator which determines the direction of the search according to the fitness score. The other is a zero-mean Guassian operator which is used as a perturbation and added to a parent in order to generate an offspring as in the

EP. Another variable “*age*” is introduced which enhances the diversity of the search and prevents individuals from remaining in the local minima. In the AEP, new parents are selected by one-to-one competition between a child and its parent.
The vector of a solution is extended for the i^{th} vector as,

$$Z^i = \left[z_1^i, \ldots, z_n^i, dir(z_1^i), \ldots, dir(z_n^i), age^i\right]^T \tag{18}$$

where $dir(z^i_j) \in \{-1,+1\}$ for all z^i_j is the evolving ‘direction” of the j^{th} parameter z^i_j in the i^{th} vector, and age^i denotes the duration of the life in an integer type in the i^{th} vector. The following two rules are employed for perturbing the parents to generate their offspring. RULE 1:

$$\begin{array}{ll} IF & f(z^i[k] < f(z^i[k-1]) \\ THEN & dir(z^i[k] = \operatorname{sgn}(z^i[k] - z^i[k-1]), \\ & age^i[k] = 1 \\ ELSE & age^i[k] = age^i[k-1] + 1 \\ & \forall i \in \{1,2,\ldots,N_p\}, \forall j \in \{1,2,\ldots n\} \end{array}$$

where $z^i_j[k]$ denotes the j^{th} parameter in the i^{th} vector at the k^{th} generation, $dir(z^i[k])$ denotes the evolving direction $z^i_j[k]$, and “sgn” is a sign function. $f(Z^i)$ is the cost function of the vector Z^i.

Based on RULE 1, the mutation occurs as follows, RULE 2:

$$\begin{array}{ll} IF & age^i[k] = 1 \\ THEN & \alpha^i = \beta_1 \cdot f(z^i[k]) \\ & z^i_j[k] = z^i_j[k-1] + dir(z^i_j) \cdot \left|N(0,\alpha^i)\right| \\ ELSE & \alpha^i = \beta_2 \cdot f(z^i[k] \cdot age^i) \\ & z^i_j[k] = z^i_j[k-1] + N(0,\alpha^i) \\ & \forall i \in \{1,2,\ldots,N_p\}, \forall j \in \{1,2,\ldots n\} \end{array}$$

where $dir(z^i_j) \cdot \left|N(0,\alpha^i)\right|$ is the realization of a Guassian distributed random variable which is polarized in the direction of $dir(z^i_j)$ and □ $_i$, i □ 1,2, are positive constants.
The above mentioned six EP methods have been applied to two examples on this test system. In the first case, multiple fuel optimization problem has been solved without considering valve point effects. While in the second case study, multiple fuel optimization problem has been solved considering valve point effects.

V. CASE STUDIES

A. **Test Case I**

This test case, adapted from [1] and [6], comprises ten generating units with non-smooth cost functions considering multiple fuel options. The total system demand is varied from 2400 MW to 2700 MW with 100 MW increments.

Parameters:

The choices of parameters for various EP methods are given as follows: Population size = 50

Maximum generations = 1000
Each individual P_j contains 10 generator power outputs, such as P_1, P_2, P_3,…and P_{10}, which are generated randomly. The dimension of the population is equal to 10x50.

The experimental results are shown in Tables I, which also satisfy the system constraints for P_D= 2400 MW – 2700 MW. IFEP has the highest probability of achieving better solutions followed by FEP; however, the convergence rate and solution time of IFEP in achieving the minimum cost is slightly slower than FEP because of increased mutation time. CEP showed the poorest performance amongst the six EPs in terms of convergence rate and observed likelihood of attaining the minimum cost. MEP converged faster and attained lower minimum cost than CEP and FEP methods. The AEP achieves a better solution quality and convergence than the other EP methods. The Fig.3 shows the convergence of AEP for different demand levels.

TABLE-I Comparison of EP Methods

Methods	Minimum Cost ($)			
	PD = 2400 MW	PD = 2500 MW	PD = 2600 MW	PD = 2700 MW
CEP	480.2481	524.7676	572.9876	622.3318
FEP	480.2417	524.7598	572.8923	622.3217
MFEP	480.2278	524.7430	572.8837	622.3173
IFEP	480.2254	524.7412	572.8828	622.3125
MEP	480.2244	524.7388	572.8819	622.3099
AEP	**480.2100**	**524.7356**	**572.8724**	**622.3005**

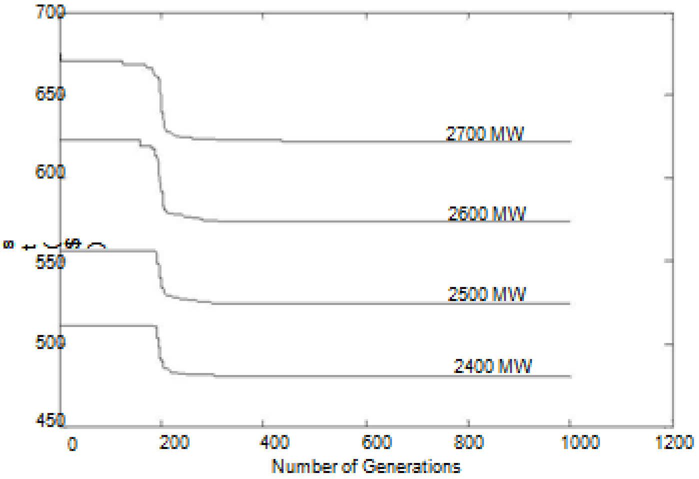

Fig.3. Convergence of AEP for different demand levels

(B) Test Case II

Test case II is the economic dispatch problem with non-smooth cost functions considering both valve point effects and multiple fuel options. The same bench mark problem is considered here with the parameters as given in test case I.

Table II shows the comparisons of the results obtained by the various EP methods for 2700 MW. The AEP gives a better economic cost ($ 624.5074) than the other methods. Table III depicts the frequency of attaining a cost within the specific ranges out of 100 runs for each of
the six EP algorithms with 100 different trial solutions for P_D=2700 MW. The compared results are also itemized in

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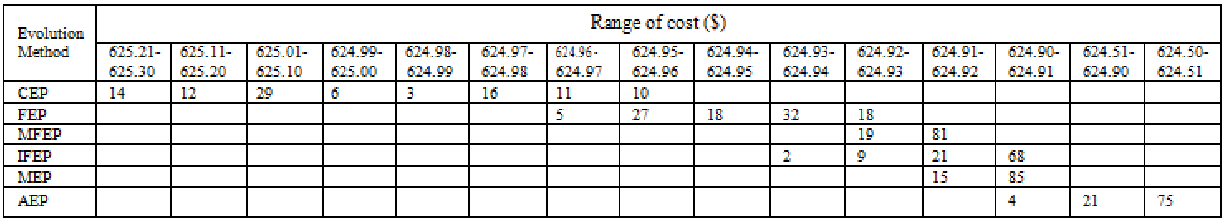
Table IV. It shows the maximum cost, mean cost and minimum cost achieved by CEP, FEP, MFEP, IFEP, MEP and AEP methods. Table III reveals that AEP method has provided the global solution with a high probability to demonstrate its effectiveness and efficiency. Moreover, as shown in Table IV, AEP has a better economic cost than the other methods. Therefore, Tables III and IV clearly show that the AEP is more robust than the other methods. The Fig.4 shows the comparison of EP methods with AEP for P_D = 2700 MW. AEP converged faster and attained lower minimum cost than any other methods.

TABLE-II
Comparison of EP Methods (P_D= 2700 MW)

Unit	CEP		FEP		MFEP		IFEP		MEP		AEP	
(j)	k	P (MW)	k	P (MW)	k	P (MW)	k	P (MW)	k	P (MW)	k	P (MW)
1	2	225.5602	2	221.5854	2	219.7551	2	220.9376	2	219.9962	2	218.2499
2	1	211.5180	1	212.2371	1	213.1851	1	212.6096	1	212.7648	1	211.6626
3	1	283.5344	1	282.7309	1	284.0275	1	283.5811	1	283.7391	1	280.7228
4	3	241.2873	3	239.2387	3	240.4534	3	240.0089	3	240.5205	3	239.6315
5	1	282.9452	1	282.0070	1	282.9303	1	282.8920	1	282.3127	1	278.4972
6	3	241.0563	3	240.6119	3	239.9359	3	240.4739	3	240.5387	3	239.6315
7	1	290.4849	1	293.9857	1	292.2646	1	292.9792	1	293.0846	1	288.5845
8	3	239.3561	3	241.1574	3	240.2247	3	240.1989	3	240.2886	3	239.6315
9	3	406.6017	3	406.9181	3	406.9599	3	406.9988	3	406.9797	3	428.5216
10	1	277.6558	1	279.5280	1	280.2634	1	279.3199	1	279.7752	1	274.8667
Total		2699.9999		2700.0002		2699.9999		2699.9999		2700.0001		2699.9998
Cost($)		625.0874		624.9370		624.9218		624.9064		624.9035		**624.5074**

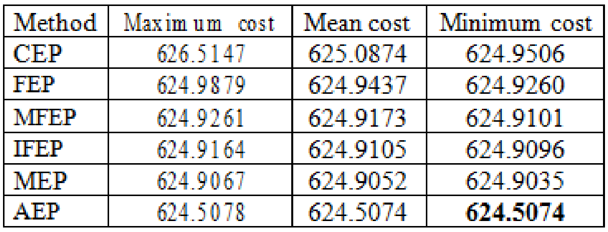
TABLE-III

Comparisons of the different EP methods on Relative Frequency of Convergence in the Ranges of Cost



Evolution Method	Range of cost ($)														
	625.21-625.30	625.11-625.20	625.01-625.10	624.99-625.00	624.98-624.99	624.97-624.98	624.96-624.97	624.95-624.96	624.94-624.95	624.93-624.94	624.92-624.93	624.91-624.92	624.90-624.91	624.51-624.90	624.50-624.51
CEP	14	12	29	6	3	16	11	10							
FEP							5	27	18	32	18				
MFEP											19	81			
IFEP										2	9	21	68		
MEP												15	85		
AEP													4	21	75

TABLE-IV
Comparison of simulation results



Method	Maxim um cost	Mean cost	Minimum cost
CEP	626.5147	625.0874	624.9506
FEP	624.9879	624.9437	624.9260
MFEP	624.9261	624.9173	624.9101
IFEP	624.9164	624.9105	624.9096
MEP	624.9067	624.9052	624.9035
AEP	624.5078	624.5074	**624.5074**

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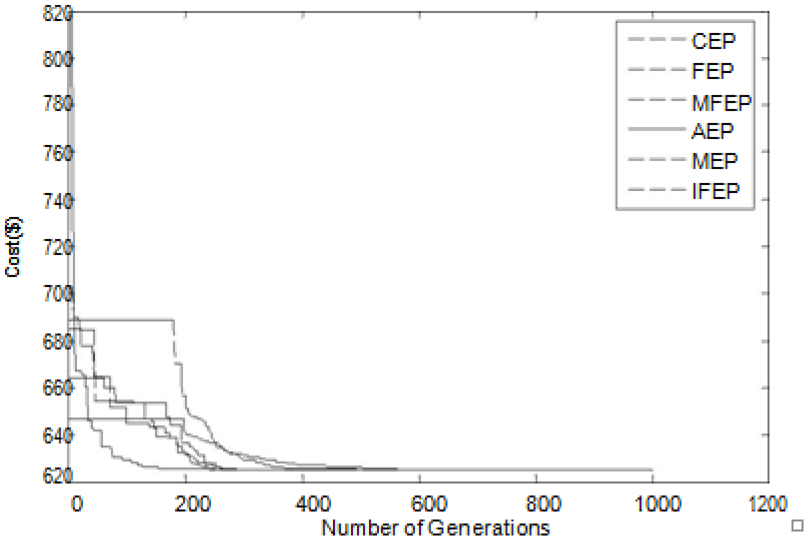

Fig.4. Comparison of EP methods with AEP for PD = 2700 MW

Fig.4. Comparison of EP methods with AEP for PD = 2700 MW

In [13] IGA_MU method results are compared with HM, HNN, AHNN, EP and CGA_MU methods for 2700 MW demand. The AEP results are compared with CGA_MU and IGA_MU and given in Table V. The proposed algorithm also yields better solution quality than other methods, and is more efficient and effective than the CGA_MU and IGA_MU in the economic dispatch problem. Table V shows the comparisons of the results obtained by AEP with IGA_MU and CGA_MU [13]. The AEP gives a better economic cost ($ 624.5074) than the other methods.

TABLE-V
Comparison of Optimization Methods (P_D= 2700 MW)

Unit	CGA-MU		IGA-MU		AEP	
(j)	P (MW)	Fuel	P (MW)	Fuel	P (MW)	Fuel
1	222.0108	2	219.1261	2	218.2499	2
2	211.6352	1	211.1645	1	211.6626	1
3	283.9455	1	280.6572	1	280.7228	1
4	237.8052	3	238.4770	3	239.6315	3
5	280.4480	1	276.4179	1	278.4972	1
6	236.0330	3	240.4672	3	239.6315	3
7	292.0499	1	287.7399	1	288.5845	1
8	241.9708	3	240.7614	3	239.6315	3
9	424.2011	3	429.3370	3	428.5216	3
10	269.9005	1	275.8518	1	274.8667	1
Total	2700.0000		2700.0000		2699.9998	
Cost($)	624.7193		624.5178		**624.5074**	

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VI. CONCLUSION

Few reports have been made at units considering both valve-point effects and multiple fuels for the realistic economic dispatch problem, which always exist in real power systems simultaneously. In this paper six different evolutionary programming techniques demonstrated to solve such practical economic dispatch operation. It is observed that EP techniques are capable of finding the optimal or near optimal solutions even for economic dispatch problems with any type of cost functions. However, the performance of the AEP approach provides better solution than all other EP techniques in terms of convergence rate, solution time, minimum cost and probability. However, the constraints like ramp rate limit, security constraints are not considered in this paper. Moreover, the AEP gives better solution than the CGA_MU and IGA_MU methods. Simulation results demonstrate that the AEP approach can give a cheaper total generation cost than any other considered methods.

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