Short-term Generation Scheduling with Take-or-pay Fuel Contract using an Evolutionary Programming Technique

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This paper describes an evolutionary programming based optimization technique for solving the short-term generation scheduling problem with take-or-pay fuel contract. The load constraints, operation constraints and the fuel constraints are fully taken into account, and the proposed methodology handles them effectively. The methodology described in this paper is a general methodology based on evolutionary programming technique which is capable of providing the global optimum generation schedule under take-or-pay fuel contract irrespective of any kind of heat-rate functions including the effect of valve-point loadings. The solution methodology is demonstrated through a test example, in which the generation loadings of a fuel-constrained and an equivalent steam unit are scheduled in a 24-h schedule horizon. The proposed method has been applied to the various test cases and the results obtained are discussed. The evolutionary programming based technique in obtaining optimal generation dispatch can considerably make the automatic generation control strategy convenient and less time consuming.

Keywords : Short-term generation scheduling; Take-or-pay fuel contract; Gas-fired steam plant; Valve-point loading; Evolutionary programming technique

INTRODUCTION

The short-term generation scheduling with take-or-pay fuel contract is gaining importance in recent years. The utility is required to pay a minimum charge to the fuel supplier if a minimum amount of fuel is not consumed for a period under the take-or-pay fuel contract. Therefore, this aspect of the take-or-pay contract needs to be considered in the determination of the most economical generation schedule over a period. However, this aspect of take-or-pay need not be considered for a fuel-constrained generator, if the amount of fuel consumed by this generator is more than the minimum specified amount. In this situation, the determination of the loading of such a generator amongst those of other generators is simply an economic dispatch problem. The most economic generation schedule under take-or-pay fuel contract has been solved by conventional methods based on Lagrange multiplier and on gradient descent[2]. But these methods have inherent difficulties in dealing with the operation limits and the non-convexity of the incremental heat-rate curves of the generators. Further, these conventional methods may not be appropriate for accurate short-term generation scheduling as the incremental heat-rate curves of thermal generators can be non-monotonic due to the effects of valve-point loading[3]. Therefore, there is a strong need to develop a more general technique for solving the generation scheduling problem with take-or-pay fuel contract. Wong, *et al* have reported a generalized method for solving such problem[4]. However, they have developed an algorithm by combining genetic algorithm, simulated annealing as well as fuzzy set approach which seem to be very rigorous as well as time-consuming. In recent years, another powerful optimization technique called as evolutionary programming (EP) is being continuously applied on various power system optimization problems due to its more powerful ability in finding the global optimum solutions as compared to genetic algorithm or simulated annealing technique. Yang, *et al* have developed an efficient general economic dispatch algorithm for units with non-smooth fuel cost functions based on EP technique[5]. In this work, the results of ED problems when solved by genetic algorithm, simulated annealing and EP have been compared. They have shown that the EP method is able to give a cheaper schedule at a less computation time. Hanzheng, *et al*, described a solution method for unit commitment using Lagrangian relaxation combined with evolutionary programming[6]. Hota, *et al* have developed an evolutionary programming based algorithm for solution of short-term hydrothermal scheduling problem[7]. They have also shown that when compared to simulated annealing based algorithm for short-term hydrothermal scheduling, EP based algorithm is able to obtain a cheaper hydrothermal schedule at reduced execution time. Initially the simple problem formulation of a short-term generation scheduling problem with take-or-pay fuel contract is discussed and then an algorithm based on a global optimization technique, such as, evolutionary programming (EP) technique has been described. A test system with various test cases is solved by the proposed EP based algorithm. To validate the accuracy and applicability of EP

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based method, the results obtained from this method are compared with those obtained from the conventional gamma search method[2] for the case of smooth characteristic functions of the generating units only. A detailed problem formulation with global optimization based solution technique has been addressed which can handle the more general short-term generation scheduling with take-or-pay fuel contract where, any kind of heat-rate curves of generators (*eg*, non-convex due to valve-point loadings) can be solved efficiently.

TAKE - OR- PAY FUEL SUPPLY CONTRACT

It is assumed that there are *N* normally fueled thermal plants plus one turbine generator, fueled under a take-or-pay agreement. This type of agreement will be interpreted as being one in which the utility agrees to use a minimum amount of fuel during a period (the 'take') or, failing to use this amount, it agrees to pay the minimum charge. This last clause is the 'pay' part of the take-or-pay contract. While this unit's cumulative fuel consumption is below the minimum, the system excluding this unit should be scheduled to minimize the total fuel cost, subject to the constraint that the total fuel consumption for the period for this particular unit is equal to the specified amount. Once the specified amount of fuel has been used, the unit should be scheduled normally. A special case is considerd, where the minimum amount of fuel consumption is also the maximum. This seems to be realistic since, normally the fueled generators under take-or-pay agreement are costlier than the ordinary thermal generators and no one would like to run the fueled generators under take-or-pay agreement to their maximum loadings due to the increased costs.

Problem Formulation

The basic short-term generation scheduling problem with one fuel-constrained generator (gas-fired unit) and an equivalent normally-fuelled generator (steam unit) with a take-or-pay fuel contract is described mathematically as given here.

$$\text{Minimize } F = \sum_{j=1}^{J} n_j f_{sj}(P_{sj}) + F_T \quad (1)$$

In which J is the total number of intervals in the scheduled horizon. The number of hours in the j^{th} interval is nj. The fuel cost of equivalent steam unit with loading P_{sj} in the j^{th} interval is $n_j f_{sj}(P_{sj})$. F_T is the total cost of running the fuel-constrained generator in the schedule horizon and it is given by

$$F_T = \left\{ \max\left(C_t, \sum_{j=1}^{J} n_j f_{gj}(P_{gj})\right)\right\} \quad (2)$$

where C_t is the contracted take-or-pay fuel cost of fuel-constrained generator. Ignoring the loss aspect, the minimization of equation (1) is subjected to the power balance constraint as given here.

$$D_j = P_{sj} + P_{gj},\ j = 1, 2, \ldots, J \quad (3)$$

where, P_{sj} and P_{gj} are the loadings of normally-fuelled generator and fuel-constrained generator, respectively, and

D_j is the load demand in interval j.

It is also subjected to the constraints imposed by the minimum and maximum operation limits of both the generators, which are given as

$$P_s^{min} \le P_{sj} \le P_s^{max} \text{ for } j = 1, 2, \ldots, J \quad (4)$$

and

$$P_g^{min} \le P_{gj} \le P_g^{max} \text{ for } j = 1, 2, \ldots, J \quad (5)$$

where, P_{sj} is power from equivalent steam unit in the j^{th} time interval, P_{gj}, the power from gas-fired unit in the j^{th} time interval, P_s^{min}, P_s^{max} are the minimum and the maximum power generation limit of equivalent steam unit and P_g^{min}, P_g^{max} are minimum and maximum power generation limit of gas-fired unit, respectively,

EVOLUTIONARY PROGRAMMING BASED APPROACH

Evolutionary programming is a powerful general-purpose technique for solving complex real-world optimization problems[8-9]. It is a stochastic optimization technique and can search for global optimum solution. Like genetic algorithm (GA), this technique works on population of trial solutions, imposes random changes to those solutions to create offsprings, and incorporates the use of selection to determine which solutions to maintain into future generations and which are to be removed from the pool of trials[10].

EP Algorithm

The general scheme of the EP algorithm for optimization (minimization task) is summarized in the following steps.

Step 1

The problem variables to be determined, are represented as a trial n-dimensional vector x, where each vector x is an individual of the population to be evolved.

Step 2

To choose randomly an initial population of parent vectors x_i, $i = 1, \ldots, N_P$, from a feasible range in each dimension. The distribution of these initial parent vectors is typically uniform. Then, to set iteration count I = 1.

Step 3

To generate an offspring vector, x_i', $i = 1, \ldots, N_P$, from each parent x_i by adding a Gaussian random variable with zero mean and preselected standard deviation to each component of x_i.

Step 4

To evaluate the functions f(x_i) and f(x_i'), $i = 1, \ldots, N_P$.

Step 5

To choose randomly a competitor x_c from the competing pool consisting of $2N_P$ trial solutions (N_P parents and their corresponding N_P offsprings). Then to perform a stochastic competition based on the functions f(x_i) and f(x_i'), where each individual in the competing pool compete against other members for survival.

Step 6

To select the N_P trial solution vectors with the minimum function values according to a decision rule to form a survivor set. The individuals in the survivor set are new N_P parents for the next generation.

Step 7

If $I < I_{max}$ then go to *step 3*.

Step 8

The output is the global optimal solution after the predefined number of iterations reached.

PROBLEM FORMULATION BY EP APPROACH

The following formulation is proposed for solving the short-term generation scheduling problem with take-or-pay fuel contract. First select arbitrarily a time interval '*d*' in the schedule horizon. Let the unknown generation from normally-fuelled generator, P_{sd} in the d^{th} time interval be the dependent generation. The P_{sd} can be calculated by assuming that the generations from normally-fuelled generator in the non-dependent intervals, *ie*, P_{sj} for j = 1,2, …, J but $j \neq d$, are known. In order to obtain the P_{sj}, the generation of the fuel-constrained generator in the dependent interval, P_{gd}, is required to be calculated.

Determination of P_{gd} and P_{sd}

When fuel-constrained generator consumes the agreed minimum fuel, its fuel cost in the dependent interval is given by

$$f_{gd}(P_{gd}) = \left(C_t - \sum_{j=1, j \neq d}^{J} n_j f_{gj}(P_{gj})\right) / n_d \qquad (6)$$

where, the summation term is the total fuel cost of fuel-constrained generator less that in dependent interval d and C_t is the cost if the fuel consumption is less than or equal to the agreed minimum. The fuel cost $f_{gd}(P_{gd})$ is also given by the fuel cost function of fuel-constrained generator. If the fuel cost function is a quadratic function, P_{gd} can be found by solving the fuel cost quadratic function using equation(6). However, if the fuel cost function is highly non-linear owing to the turbine-valving effects, multiple solution values for P_{gd} can exist. To find the solution values of P_{gd}, the fuel cost equation may be solved iteratively starting with different initial values of P_{gd}. For the iterative method to be successful, guidelines for estimating the initial values are required. Unfortunately, such guidelines do not exist. Therefore, an efficient method based on fuzzy set is proposed to solve this, which is described next. After obtaining the P_{gd}, the generation from the normally-fuelled generator in the dependent interval, *ie*, P_{sd} can be calculated from equation (3) as

$$P_{sd} = D_d - P_{gd} \qquad (7)$$

The generations from fuel-constrained generator in the non-dependent intervals are then obtained by solving the following equation.

$$D_j - P_{sj} - P_{gj} = 0 \text{ for } j = 1, 2, \ldots, (d-1), (d+1), \ldots, J \qquad (8)$$

All the generation levels must be checked against their limiting values.

Determination of P_{gd} Using Fuzzy Set Approach

Considering Z be a collection of elements denoted by x, a fuzzy set F in Z is a set of ordered pairs[11].

$$F = \left\{ (x, \mu_F(x)) \mid x \in Z \right\} \qquad (9)$$

where, $\mu_F(x)$is the membership function of element x. The membership function $\mu_F(x)$ gives the degree of truth of x in the fuzzy set F. If the degree of truth is graded within 0 and 1, then the fuzzy set F maps Z to the membership space between 0 and 1. The membership function $\mu_F(x)$ in equation(9) becomes $\mu_F(n_d f_{gd}(P_{gd}))$ and it will give the measure of the closeness of the total fuel cost of fuel-constrained generator in the whole of the schedule horizon to the contracted take-or-pay fuel cost. As suggested by Bellman and Zadeh[12], the following membership function is adopted in the present work for grading the closeness of the value of a number n to a prespecified value, V_{sp}.

$$\mu(n) = \left(1 + (n - V_{sp})^4\right)^{-1} \qquad (10)$$

Then the membership function $\mu_F(n_d f_{gd}(P_{gd}))$ is defined as

$$\mu_F(n_d f_{gd}(P_{gd})) = \left(1 + \left(\left(\sum_{j=1, j \neq d}^{J} n_j f_{gj}(P_{gj}) + n_d f_{gd}(P_{gd})\right) - C_t\right)^4\right)^{-1} \qquad (11)$$

The function in equation (11) is more superior than the ordinary triangular membership function, because it is a continuous function which covers the whole range of values of P_{gd} and it assigns high membership values to the values of P_{gd} only when they are very close to C_t. The operation range of fuel-constrained generator is divided into m equal sub-ranges. In the present work, the operation range is divided into five sub-ranges. For each sub-range, a value within the sub-range is chosen arbitrarily and is assigned to be the value of P_{gd}. The value of the membership function $\mu_F(n_d f_{gd}(P_{gd}))$ corresponding to a value of P_{gd} is then calculated using equation (11). The P_{gd} value which gives the largest value of $\mu_F(n_d f_{gd}(P_{gd}))$ in the operation range of fuel-constrained generator is accepted.

The structure of the short-term generation scheduling with take-or-pay fuel contract solved by the EP technique is described in shape of a flow-chart which is shown in Figure 1. The initial values of all components (non-dependent generations from normally-fuelled generator) of each parent as well as the associated dependent generation from normally-fuelled generator are specified or generated at random before starting the process of evolution. Assuming the initial value of the dependent generation of normally-fuelled generator, the fuel-constrained generation in the dependent interval is computed. Consequently, the dependent generation of normally-fuelled generator, generations of normally-fuelled generator and fuel-constrained generator in the non-dependent intervals are calculated. Thereafter, all the generation levels are checked against their corresponding limits and the total contracted fuel for the fuel-constrained generator is checked. If all the constraints are satisfied, then the current generations of normally-fuelled generator in the non-dependent intervals are taken as the components of the final feasible parent. If otherwise, then using the current value of the dependent generation of the normally-fuelled generator, all the generation levels are again calculated and all the constraints are checked till all of them are satisfied. The process of generating feasible parent vectors continues till the iteration count equals N_P. Similar checking of constraints is performed for generation of each feasible offspring. At the end of the solution process the trial vector with minimum function value among the N_P trial vectors will be the global optimum solution.

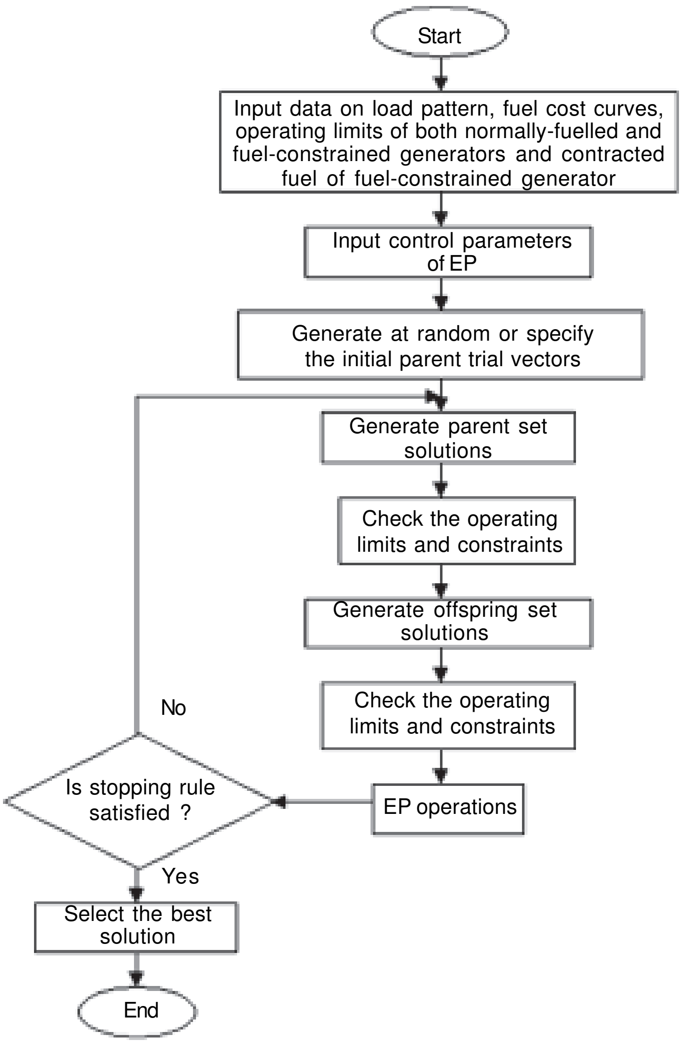

Figure 1 The structure of the EP based methodology for short-term generation scheduling with take-or-pay fuel contract

APPLICATION EXAMPLE

The test system is adopted from Wood and Wolenberg[2]. It consists of a gas-fired plant and an equivalent steam plant. The gas-fired plant is the fuel-constrained generator and the equivalent steam plant is the normally-fuelled generator. The gamma search method was applied to this test system to determine the optimum economic schedule[2]. The schedule horizon is 24 h and there are six four-hour intervals. The load demands in the intervals are summarized in Table 1.

The proposed EP approach is applied to three different cases to prove its usefulness. Prior to applying the EP approach to the short-term generation scheduling problem with take-or-pay fuel contract having non-linear fuel cost curves of the generators, it has been initially applied to the problem with quadratic fuel cost curves of the generators to prove its satisfactory working. The three different cases considered are as follows.

Case 1

In this case the fuel cost function of the gas-fired unit is

$$f(P_g) = 300 + 8.5P_g + 0.0025P_g^2 \text{ MBtu/h} \quad (12)$$

and the fuel cost function of the equivalent steam unit is

$$f(P_s) = 200 + 8.5P_s + 0.002P_s^2 \text{ MBtu/h} \quad (13)$$

Case 2

In this case the fuel cost function of the equivalent steam unit remains the same as in case 1. However, the fuel cost function considering the valve point effect is employed for the gas-fired unit to test the performance of the proposed EP approach. To simulate the valve-point loading, a sinusoidal component is superimposed on the quadratic fuel cost function. In the present work, the fuel cost function of

Table 1 Intervals and load demands in schedule horizon

Interval number	Interval	Demand, MW
1	12 pm – 4 am	400
2	4 am – 8 am	650
3	8 am – 12 am	800
4	12 am – 4 pm	500
5	4 pm – 8 pm	200
6	8 pm – 12 pm	300

the gas-fired unit is taken as

$$f(P_g) = 300 + 6.0P_g + 0.0025P_g^2 + \left|100 \sin(0.084(P_g^{min} - P_g))\right| \text{MBtu/h} \quad (14)$$

Case 3

In this case the fuel cost functions considering the valve point effects are employed for both the generators to test the performance of the proposed EP approach. The fuel cost function of the gas-fired unit remains the same as in case-2. However, the fuel cost function of the equivalent steam unit is taken as

$$f(P_s) = 200 + 8.5P_s + 0.002P_s^2 + \left|150 \sin(0.063(P_s^{min} - P_s))\right| \text{MBtu/h} \quad (15)$$

The lower and upper operation limits of the gas-fired unit are 50 MW and 400 MW, respectively. The fuel cost for gas is 2.0 R/10^3 ft^3 and the gas is rated at 1100 Btu/ft^3. This unit must burn 40×10^6 ft^3 of gas which is the agreed amount of total gas consumption over the schedule horizon. The lower and upper operation limits of the equivalent steam unit are 50 MW and 500 MW, respectively. The fuel cost is 0.6 R/Mbtu.

The optimum economic generation schedule of the case 1 under take-or-pay fuel contract was determined by the proposed EP based method and the results are shown in Table 2. In the same table, the results obtained from the gamma search method[2] are compared with the results those obtained from EP based method. From this table, it is found that almost identical were obtained by the proposed EP based and SQP methods. This indicates that the proposed EP based method can obtain the optimum short-term generation schedule under take-or-pay fuel contract accurately.

The optimum generation schedules for case 2 and case 3 are determined by the proposed EP based method and the results are summarized in Table 3. It is to be noted that in determining the optimum generation schedule by EP based method for case 1, the P_{gd} is determined by simple algebraic method but the same is determined by proposed fuzzy set approach for case 2 and case 3.

Table 2 Determined generation schedule and operating costs for case 1

Method	Interval	Optimum generations, MW		Operating costs, R	
		Steam unit	Gas-fired unit	Steam unit	Gas-fired unit
Gamma search method (Ref 2)	12 pm - 4 am	197.300	202.600		
	4 am - 8 am	353.200	296.800		
	8 am -12 am	446.700	353.300		
	12 am - 4 pm	259.700	240.300		
	4 pm - 8 pm	72.600	127.400		
	8 pm -12 pm	135.000	165.000	34937.47	80000.00
Proposed EP based method	12 pm - 4 am	197.3483	202.6517		
	4 am - 8 am	353.2106	296.7894		
	8 am - 12 am	446.7282	353.2718		
	12 am - 4 pm	259.6931	240.3069		
	4 pm - 8 pm	72.6584	127.3416		
	8 pm - 12 pm	135.0031	164.9969	34938.92	80000.00

Table 3 Determined generation schedule and operating costs for case 2 and case 3 by proposed EP method

Case	Interval	Optimum generations, MW		Operating costs, R	
		Steam unit	Gas-fired unit	Steam unit	Gas-fired unit
Case 2	12 pm - 4 am	275.2001	124.7999		
	4 am - 8 am	263.4007	386.5993		
	8 am -12 am	413.3986	386.6014		
	12 am - 4 pm	188.1997	311.8003		
	4 pm - 8 pm	149.9995	50.0005		
	8 pm -12 pm	208.3652	91.6348	35453.97	80000.00
Case 3	12 pm - 4 am	312.6001	87.3999		
	4 am - 8 am	263.4010	386.5990		
	8 am -12 am	449.5946	350.4054		
	12 am - 4 pm	188.2007	311.7993		
	4 pm - 8 pm	99.8673	100.1327		
	8 pm -12 pm	199.6006	100.3994	36728.01	80000.00

The total cost of the schedule determined by proposed EP technique when the valve point loading effects of the generators are not considered (case 1) is found to be R 114938.92. The total cost of the schedule determined by the proposed EP based technique when the valve point loading effect of the gas-fired unit is taken into account (case 2) is found to be R 115453.97. This cost is 0.45% higher than that obtained in case 1. Similarly, the total cost of the schedule determined by EP based technique is R 116728.01, when the valve point loading effects of the both generators are taken into account (case 3). This cost is 1.15% higher than that obtained in case 1. This indicates that when valve-point loading is considered, the total fuel cost is generally higher. Although being tested on a small system, the EP based methodology described in this dissertation work should be applicable to large systems having perhaps hundreds of constraints and as many or more problem variables. In applying the developed algorithm to the test cases, the initial values of all components (non-dependent normally-fuelled generations) of each parent as well as the associated dependent normally-fuelled generation are specified or generated at random before starting the process of evolution. The control parameters of the EP algorithm are maximum iteration number, population size and scaling factor and the most appropriate values of these parameters are set to 400, 50 and 0.005, respectively. These values are obtained after testing and evaluating different combination as shown in Figure 2(a), Figure 2(b) and Figure 3(a), respectively for case 3.

In order to explore the converging characteristics of the EP, different random initial solutions were given to the proposed EP algorithm along with the control parameters mentioned here. The optimal solutions corresponding to each random initial solution (trial) are observed. Figure 3(b) shows the

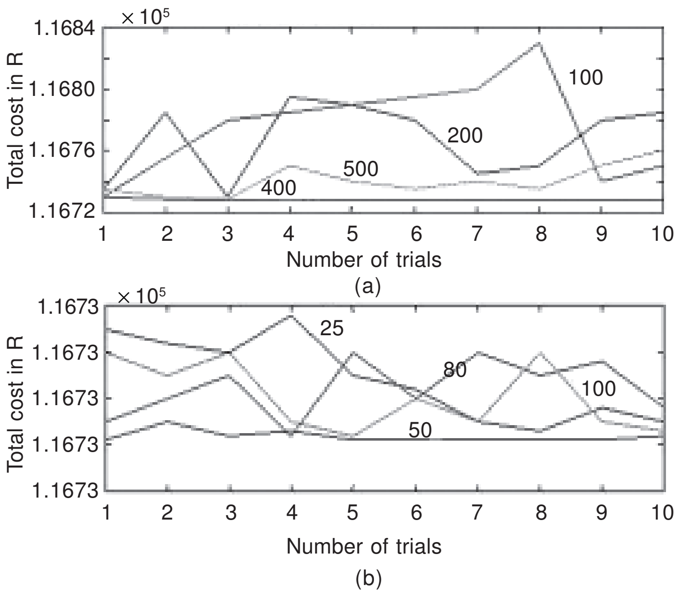

Figure 2 Determination of (a) maximum iteration number and (b) population size

total cost variation of final generation schedule with take-or-pay fuel contract obtained from proposed EP approach when executed ten times with different random initial solutions. The best cost of the optimal generation schedule is found to be R 116728.01 (global optimum solution) and the worst cost is found to be R 116735.42. It is observed from Figure 3(b) that 80% of the solutions after execution of each trial were converged approximately at the global optimum solution. This indicates that the EP technique has more powerful ability to achieve the global optimum solution. The computer programs were implemented using MATLAB 6.1 and run on a 2.4 GHz Pentium-IV PC with Windows 98 operating system. The proposed EP approach required about 4 min of total computer time to obtain the best (global optimum) short-term generation schedule with take-or-pay fuel contract for test data as mentioned in case 3.

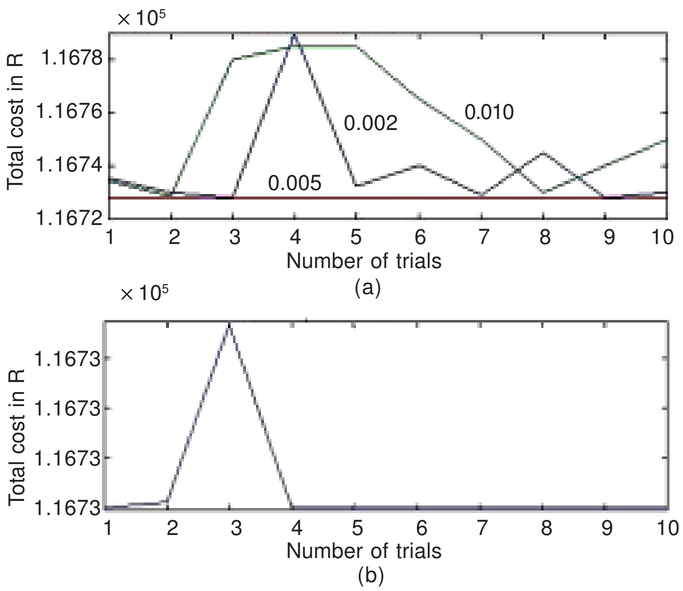

Figure 3 (a) Determination of scaling factor and (b) final cost variation

CONCLUSION

This paper describes a more general methodology based on evolutionary programming technique to obtain the global optimum generation schedule under take-or-pay fuel contract irrespective of any kind of heat-rate functions including effect of valve-point loadings. The load constraints, operation constraints and the gas constraints are fully taken into account, and the proposed methodology handles them effectively. A detailed problem formulation with global optimization based solution technique has been addressed. The solution methodology is demonstrated through a test example, in which the generation loadings of a fuel-constrained and an equivalent steam unit are scheduled in a 24 h schedule horizon. The proposed method has been applied to the various test cases and the results obtained are discussed. To validate the accuracy and applicability of EP based method, the results obtained from this method are compared with those obtained from the conventional gamma search method for the case of smooth characteristic functions of the generating units. Therefore, the proposed methodology in obtaining optimal generation dispatch can considerably make the automatic generation control strategy convenient and less time consuming.

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