Simulated Annealing Optimization for Generation Scheduling with Cubic Fuel Cost Function

ZIANE ISMAIL, BENHAMIDA FARID, AND GRAA AMEL
Department of Electrotechnics
Irecom laboratory, UDL university of Sidi Bel Abbes
Sidi Bel Abbes, P.B. 22000
ALGERIA
ziane_ismail2005@yahoo.fr, farid.benhamida@yahoo.fr, graa_amel@yahoo.fr

***Abstract:* -** In the last years, the researchers put mathematical equations to find the fuel cost from thermal plants which the variable is the power output of each plant. For this paper, we propose a cubic fuel cost function to find the minimum fuel cost in power systems. The fuel cost is described with 4 parameters. In this work, we use simulated annealing method to find the optimal solution. In this study, in order to evaluate the performance of the SA algorithm, it is tested on 4 different unit systems (3-unit, 3-unit with losses, 5-unit and 26-unit systems). The results obtained from the proposed method are compared other methods reported previously in the literature. The results show that the SA algorithm is better than the others at solving such a problem.

Key-Words: - economic load dispatch, estimation, cubic function, price penalty factor, simulated annealing.

1 Introduction

The economic load dispatch is important task in power system planning and operation. This task can be formulated mathematically as optimization problem with the objective of minimizing the fuel cost function [1]. The cost of electrical production is described with three main sources: facility construction, ownership cost, and operating costs. The operating cost is the most significant of these three, and so the focus will be on the economics of the operation [2]. The solution accuracy of economic dispatch problems is associated with the accuracy of the fuel cost curve parameters. The solution precision of the economic load dispatch is associated with the precision of fuel cost curve parameters. Therefore, updating of these parameters is a very important issue to further improve the final accuracy of economic dispatch problems [1, 2].

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The fuel cost function optimizes the total cost of active power generation, assuming that every generator has a convex cost curve related to its own active power, every generator has upper and lower active power generating limits and it is also assumed that the sum of all active powers of generator must be equal to a given total system load plus total system losses. A major challenge for all power utilities is to satisfy the consumer demand for power at minimal cost [2].

The cost function in classic ED problem is defined as a quadratic function but the cubic function can give more realistic than a quadratic function to express the operating cost.

Several strategies are proposed the fuel cost function as a quadratic function such as Evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE), particle swarm optimization (PSO) [3], have been also proved to be effective with promising performance etc. Chaotic particle swarm optimization (CPSO) [4] and new particle swarm with local random search (NPSO-LRS) [5] have been successfully applied to solve the ELD problem.

Another various evolutionary algorithms are proposed the fuel cost function as a cubic function such as genetic algorithm (GA) [6], particle swarm optimization (PSO) [6], firefly algorithm (FA) [7], pattern search (PS) [8], dynamic programming (DP) [9] and improved genetic algorithm with multiplier updating (IGA_MU) [10] methods.

In this paper, a simulated annealing (SA) algorithm is proposed to solve the economic emission dispatch problem. A generalized equation to find optimal generation that minimizes fuel cost with cubic function, which can be easily implemented for a large power system.

2 Mathematical model of fuel cost curve

. The smooth fuel cost function is defined by polynomial functions as three representations predominate:

- Linear function:

$$F_{Ci}(P_i) = a_i P_i + b_i \quad (1)$$

- Quadratic function:

$$F_{Ci}(P_i) = a_i P_i^2 + b_i P_i + c_i \quad (2)$$

- Cubic function:

$$F_{Ci}(P_i) = a_i P_i^3 + b_i P_i^2 + c_i P_i + d_i \quad (3)$$

➢ *Power balance constraints*

$$\sum P_i = P_D + P_L \quad (4)$$

where P_D is the load demand and P_L is the total transmission network losses.

➢ *Generator limit Constraints*

Generators have limits on the minimum and maximum amount of power they can produce. Often times the minimum limit is not zero. This represents a limit on the generator's operation with the desired fuel type because of varying system economics usually many generators in a system are operated at their maximum MW limits.

$$P_{i\,\min} \le P_i \le P_{i\,\max} \quad (5)$$

where $P_{i\,min}$ is the minimum generation limit of unit i and $P_{i\,max}$ is the maximum generation limit of unit i.

➢ *Power balance constraints*

$$\sum P_i = P_D + P_L \quad (6)$$

where P_D is the load demand and P_L is the total transmission network losses.

The simplest form of loss equation is George's formula, which is given by:

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} B_{ij} P_i P_j \quad (7)$$

B_{ij} is called the loss coefficient

➢ *Generator limit Constraints*

The power generation of unit i should be between its minimum and maximum limits.

$$P_{i\,\min} \le P_i \le P_{i\,\max} \quad (8)$$

where $P_{i\,min}$ is the minimum generation limit of unit i and $P_{i\,max}$ is the maximum generation limit of unit *i*.

3 Simulated Annealing Algorithm for Economic dispatch Problem

The simulated annealing method [13] is a heuristic optimization technique and it has the ability to find global or near global optimum solutions for large combinatorial optimization problems. This method is similar to the local search technique in optimization, which can only guarantee a local optimum solution. Simulated annealing is proposed in Kirkpatrick, Gelett and Vecchi in 1983 and Cerny [14] in 1985 for finding the global minimum of a cost function that may presses several local minima [15].

The name simulated annealing comes from an analogy between combinatorial optimization and the physical process of annealing. In physical annealing a solid is cooled very slowly, starting from a high temperature, in order to achieve a state of minimum internal energy. It is cooled slowly so that thermal equilibrium is achieved at each temperature. Thermal equilibrium can be characterized by the Boltzmann distribution.

$$P_{accept}\{x, y\} = \begin{cases} 1, & if\ E_X - E_Y \le 0 \\ e^{-(E_x - E_y)/k_B T}, & if\ E - E > 0 \end{cases} \quad (9)$$

3.1 Simulated Annealing algorithm

The SA algorithm for dispatch problem is stepped as follows [16]:

Initialisation

Choose an initial solution $S \in X$;

$S^* \leftarrow S$;

C ← *0*; (Global iteration count)
T ← T_0; (T_0 Initial system temperature)
Iterative Processes
Nbiter ← 0;
While (Nbiter < nb_iter)
C ← *C+1*; Nbiter ← Nbiter+1;
Generate randomly a solution $S' \in N(S)$;
ΔF ← *F(S)-F(S)*;
if *(ΔF <0)* **then**
S←S';
Otherwise
Prob (ΔF, T) ← *exp (-ΔF/T)*;
Generate q uniformly in the interval: [0,1];
If (q< prob (ΔF, T)) **then**
S ← *S'*;
If F(S) < F(S*) **then**
*S** ← *S*;
T= α T; (0 < α <1 cooling coefficient).

4 Results and Discussion

The proposed optimization algorithm is applied to a 4 unit systems to verify its effectiveness. The networks used are 3-unit, 3-unit with losses, 5-unit and 26-unit systems.
For conducting the test, the initial temperature is fixed at 10 C°, alpha is fixed at 0.99 and max tries is 10000. The final temperature is 1e-10 C°.

4.1 3-unit system

The generator cost coefficients and generation limits of 3-unit network are taken from [11] and listed in table 1. The load demand of this system is 2500 MW. The transmission power loss is neglected.

Table 1. Parameters Of 3-unit System

	a_i	b_i	c_i	d_i	P_{max}	P_{min}
P1	749.55	6.950	0.000968	1.27E-07	800	320
P2	1285	7.051	0.0007375	6.45E-08	1200	300
P3	1531	6.531	0.00104	9.98E-08	1100	275

Table 2. Comparison Of Economic Load Dispatch Result Of 3-unit System

	Wollenberg [11]	PRPGA [12]	GA [6]	PSO [6]	FA [7]	SA
P1	726.9000	724.991408	725.02	724.99	729.0682	725.01284
P2	912.8000	910.153159	910.19	910.15	906.8021	910.18417
P3	860.4000	864.855433	864.88	864.85	864.1315	864.80299
Demand (MW)	2500.1000	2500	2500	2500	2500	2500
Fuel cost ($/h)	22730.2167	22729.324579	22730.14	22729.35	22728	22729.32458

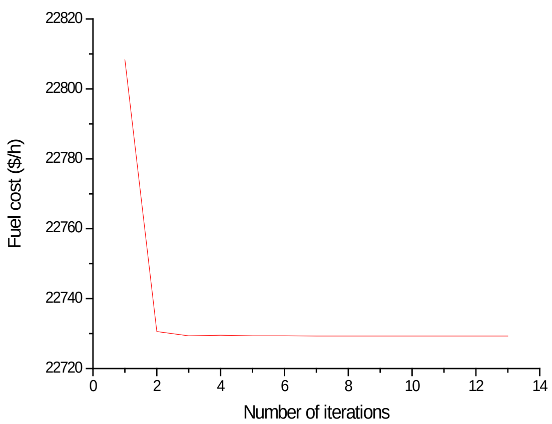

Fig 1. Convergence of fuel cost minimization (3-unit system).

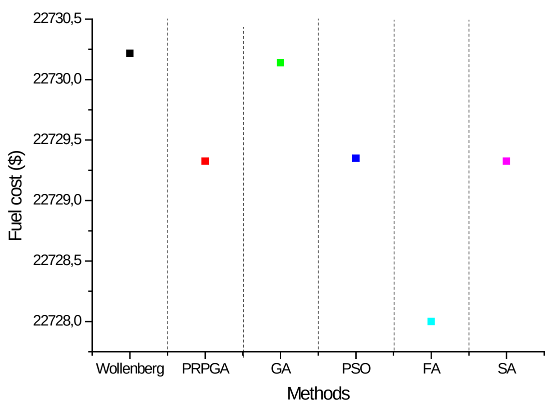

Fig 2. Comparaison of fuel cost (5-unit system).

The optimal total cost achieved by the proposed SA method is 22729.32458 $/h. The power outputs of generators 1, 2, and 3 are 725.01284 MW, 910.18417 MW, and 864.80299 MW respectively.

4.2 3-unit system with losses

The input data and B-coefficients of 3-unit with losses are taken from [12] and listed in table 3 and table 4 respectively. The load demand of this system is 1400 MW.

Table 3. Parameters Of 3-unit System

	a_i	b_i	c_i	d_i	P_{max}	P_{min}
P1	11.2	5.10238	-2.6429e-3	3.33e-06	500	100
P2	-632	13.01	-3.0571e-2	3.33e-05	500	100
P3	147.144	4.28997	3.0845e-4	-1.77e-07	1000	200

Table 4. $B_{i,j}$ Loss Parameters For 3-unit System

7.50E-05	5.00E-06	7.50E-06
5.00E-06	1.50E-05	1.00E-05
7.50E-06	1.00E-05	4.50E-05

Table 5. Comparison Of Economic Load Dispatch Result Of 3-unit System

	Liang [9]	**PS [8]**	**IGA_MU [10]**	**FA [7]**	**SA**
P1	360.2000	372.29	365.4085	362.7	359.7034
P2	406.4000	356	100	100	406.5985
P3	676.8000	712	997.3436	1000	677.1375
Demand (MW)	1400	1400	1400	1400	1400
Losses (MW)	43.4000	40.29	62.7521	62.7	43.4395
Fuel cost ($/h)	6642.2600	6639.01	6639.1849	6638.8	6642.6628

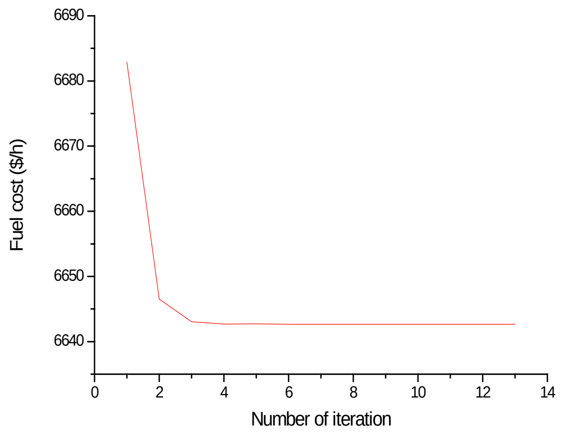

Fig 3. Convergence of fuel cost minimization (3-unit system).

The optimal total cost achieved by the proposed SA method is (6642.6628 $). The power outputs of generators 1, 2, and 3 are (359.7034 MW), (406.5985 MW), and (677.1375 MW) respectively.

4.3 5-unit system

This test system is taken from [6]. The load demand of this system is 1800 MW. Table 6 presents a comparison between SA and other methods such as GA, PSO and FA.

Table 6. Comparison Of Economic Load Dispatch Result Of 5-unit System

Unit	**GA [6]**	**PSO [6]**	**FA [7]**	**SA**
P1	320	320	327.8004	320
P2	343.74	343.7	341.989	343.9873
P3	472.6	472.6	460.4127	473.9086
P4	320	320	327.8004	320
P5	343.74	343.7	341.989	342.1032
Load (MW)	1800	1800	1800	1800
Fuel cost ($/h)	18611.07	18610.4	18610	18609.6961

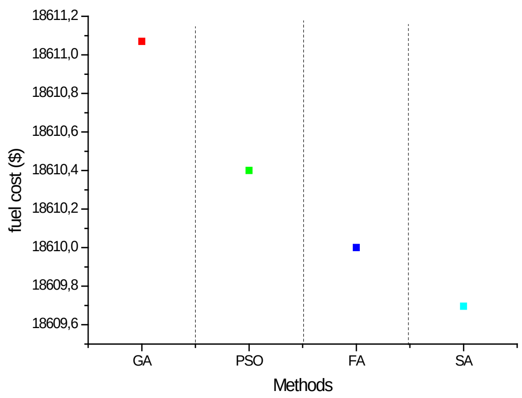

Fig 4. Comparaison of fuel cost (5-unit system).

4.4 26-unit system

The generator cost coefficients, generation limits of 26-unit system are taken from [17]. The load demand of this system is 1400 MW. Table 7 presents a comparison between SA and other methods such as GA, PSO.

Table 7. Comparison Of Economic Load Dispatch Result Of 26-unit System

Unit	GA [6]	PSO [6]	SA
P1	2.4	2.4	2.4001
P2	2.4	2.4	2.4
P3	2.4	2.4	2.4
P4	2.4	2.4	2.4
P5	2.4	2.4	2.4
P6	4	4	4
P7	4	4	4
P8	4	4	4
P9	4	4	4
P10	15.2	15.2	15.2
P11	15.2	15.2	24.9840
P12	15.2	15.2	15.2
P13	15.2	15.2	15.2
P14	25	25	25
P15	25	25	25
P16	25	25	25
P17	129.71	129.69	146.8462
P18	124.71	124.69	148.4877
P19	120.42	120.4	102.9567
P20	116.72	116.7	93.7964
P21	68.95	68.95	68.95
P22	68.95	68.95	68.95
P23	68.95	68.95	68.95
P24	337.76	337.85	327.5038
P25	400	400	399.9982
P26	400	400	399.9768
Load (MW)	2000	2000	2000
Cost ($/h)	27671.2441	27671.2276	27275.4440

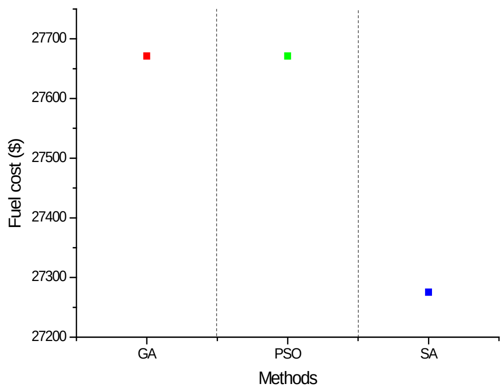

Fig 5. Comparaison of fuel cost (26-unit system).

5 Conclusions

A proposed SA method has been developed for solving constrained ELD with cubic fuel cost curve. 4 test systems are used to validate the proposed method. The studied case has cubic cost characteristics, and comparison is made with other methods in literatures. Based on the simulated results, the proposed SA method provides superior result than previously reported methods. The results show that SA is a promising technique for solving complicated problems in power system.

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