International Journal of Hybrid Information Technology
Vol.8, No. 5 (2015), pp. 215-226
http://dx.doi.org/10.14257/ijhit.2015.8.5.24

Two Lagrange Optimization Theory Based Methods for Solving Economic Load Dispatch Problems

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Abstract

The optimal generation dispatch problem with only one fuel option for each generating unit has been solved for many recent years. However, it is more realistic to represent the fuel cost function for each fossil fired plant as a segmented piece-wise quadratic functions. This is because of development of technology in thermal plants to reach maximum fuel save. Those units are faced with the difficulty of determining which the most economical fuel to burn is. This paper presents two effective methods for solving economic load dispatch problem with multiple fuel options. An advantage of the methods is to formulate Lagrange mathematical function easily based on the Lagrange multiplier theory. The proposed methods are tested on one test system consisting of ten generating units with various load demands and compared to other methods. The simulation results show that the methods are very efficient for the optimal generation dispatch problem with multiple fuel options

Keywords: *Economic load dispatch, multiple fuel options, Lagrange multiplier*

1. Introduction

In the power system planning and operation, the economic load dispatch (ELD) is meant the security of low-cost generating power as load demands according to the system constraints. This is the one of the most critical issues that has been researched recently. The single quadratic function for every generator unit prescribed basically cost function. In fact, piecewise quadratic functions is used to represent different fuels of each generator [1-4]. These functions could be solved by Lagrange method.

Three approaches to cope with the simple ELD problem are the lambda-iteration method, base point with participation factors method and gradient method. Among these mentioned methods, the first one is the fastest and most effective method. These approaches assume that the cost function for individual generators is approximately the single quadratic function. The requirement of the above tactics is the increase of fuel cost curves which are piecewise linear and monotonically. The biggest advantage of these methods is simple to apply. However, in case the cost function has more than one variable, these techniques are failed. To overcome with challenge, the Newton method has been invented. This method is much closer to the minimum generation cost in one step than three above methods [1, 5-8]. Dynamic programming method (DP) is capable of dealing with non-monotonically and discontinuous incremental cost curves. Nonetheless,

ISSN: 1738-9968 IJHIT

DP method was only accepted in the particular condition which add the ramp rate constrain of the units [1, 9-10].

To surmount these confines of conventional methods, meta-heuristic approaches have been invented. These optimal techniques based on operational research and artificial intelligence concepts. Hopfield neural networks approach has been applied to solve the non-linear ELD problem, yet had two disadvantages. The first is the selection of appropriate weighting factors for the energy function. The second is the requirement of large computational burden to obtain an optimal solution [11-12]. Simulated Annealing (SA) technique [13] is similar to a local search technique. When this technique has been applied to a real system, setting of control parameter is a difficult task, and the convergence speed is slow. Genetic algorithm (GA) [14] is the form of heuristic algorithm that mimics the process of natural evolution. This method has slow convergence near global optimum, sometimes may be trapped into local optimum. Evolutionary programming (EP) [15-17] is similar to genetic algorithm, tends to generate more effective and efficient than GA. However, both of GA and EP take long simulation time. Particle swarm optimization (PSO) [5] is motivated by the simulation of social behavior of animal such as fish schooling and bird flocking. Although PSO can converge quickly towards the optimal solution, it has difficulties in reaching a global optimum and suffers from premature converge. Moreover, PSO has several control parameters. The convergence of the algorithm depends heavily on the value of its control parameters [18-19]. A novel optimization approach, Artificial Immune System (AIS) [20] has been applied the ELD problem. This approach utilizes the colonial selection principle and evolutionary approach wherein cloning of antibodies is performed followed by hyper mutation.

The convergence of these meta-heuristic may become the local optimum with long computational time when they deal with large-scale problems. The hybrid methods can overcome the main drawback from these methods. To utilize the advantages of the element methods integrated in the hybrid methods is aim of them. Some of these approaches in literature include Simulated Annealing – Particle Swarm Optimization (SA-PSO) [21], Quantum-inspired version of the PSO using the harmonic oscillator (HQPSO) [22], Self-organizing hierarchical particle swarm optimization (SOH-PSO) [23], Bacterial foraging with Nelder-Mead algorithm (BF A-NM) [24], Adaptive Particle Swarm Optimization (APSO) [25], Uniform design with the genetic algorithm (UHGA) [26], Particle Swarm Optimization with chaotic and Gaussian approach (PSO-CG) [27], Self Tuning Hybrid Differential Evolution (STHDE) [28], variable Scaling Hybrid Differential Evolution (VSHDE) [29], Improved genetic algorithm with multiplier updating (IGAMU) [30], Differential evolution with sequential quadratic programming (DEC-SQP) [31], and Improved fast evolutionary programming (IEEP) [32]. Although the hybrid method can be better than the single approach, they can be slower.

In this paper, two effective methods based on the Lagrange multiplier theory are proposed in order to solve ELD problem. The advantage of the methods is that they are easy to formulate the problem mathematically from input data. An initial value of incremental cost is selected. In order to demonstrate the effectiveness of the proposed methods, they are tested on one test system having ten generating units with various load demands and compared to the methods such as Hierarchical Method (HM) [33], Hopfield Neural Network (HNN) [34], adaptive Hopfield neural network (AHNN) [35], Improved Evolutionary Programming (IEP) [36], Modified Particle Swarm Optimization (MPSO) [37], Improved Fast Evolutionary Programming (IFEP) [38], Fast Evolutionary Programming (FEP) [38], Classical Evolutionary Programming (CEP) [38], and Enhanced Augmented Lagrange Hopfield Network method (EALHN) [39].

The organization of this paper is as follows. The next section of the paper presents the formulation of problem. The proposed methods are presented in section III. Case studies are followed in Section IV. Finally, the paper ends in Section V with a brief discussion on results.

2. Problem Formulation

Consider a power system consisting of N generating units, each loaded to P_D MW. The generating units should be loaded in such a way that minimizes the total fuel cost C_T while satisfying the power balance and other constraints. In order to formulate the problem mathematically, the following notation is first introduced:

C (P_{Tmi}): Fuel cost of thermal plant, in (Rs/h).

i: Index of generating units;

k: Index of fuel types;

I: Number of times

M: Number of fuel types of the generating unit get the most fuel types.

m: Index of thermal plant, m=1, 2,...,M

N: Number of online generating units;

a_{ik}, b_{ik}, c_{ik}: Cost coefficients of ith generating unit with kth fuel type.

P_D: Load demand of the system, in MW.

P_i^{min}, P_i^{max} : Minimum and maximum generation level of ith generating unit, in MW.

λ: Lagrange multiplier.

P_L: Total network loss of the system, in MW;

P_{ik}: Power of the ith generating unit with the kth fuel type, in MW;

The objective of the ED problem with multiple fuel options is only to minimize the total cost of thermal generating units while satisfying different constraints including power balance and generation limits.

Mathematically, the problem is formulated as follows:

$$\text{Min } F = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

Where:

$$F_i(P_i) = \begin{cases} a_{i1} + b_{i1}P_i + c_{i1}P_i^2, \text{ fuel } 1, P_{i,min} \le P_i \le P_{i1,max} \\ a_{i2} + b_{i2}P_i + c_{i2}P_i^2, \text{ fuel } 2, P_{i2,min} \le P_i \le P_{i2,max} \\ \cdots \\ a_{ij} + b_{ij}P_i + c_{ij}P_i^2, \text{ fuel } j, P_{ij,min} \le P_i \le P_{ij,max} \end{cases} \tag{2}$$

when the valve point effect of thermal units are considered, fuel cost function for fuel type *j* of unit *i* is determined by:

$$F_i(P_i) = a_{ij} + b_{ij}P_i + c_{ij}P_i^2 \tag{3}$$

Subject to:

- *Power balance constraints:* the power generated by all thermal units must be equal to load demand

$$\sum_{i=1}^{N} P_i - P_D = 0 \tag{4}$$

- *Generator operating limits*:

$$\begin{aligned} &P_{i1}^{\min} \le P_{i1} \le P_{i1}^{\max} \quad for\ fuel\ 1 \\ &P_{i2}^{\min} \le P_{i2} \le P_{i2}^{\max} \quad for\ fuel\ 2 \\ &\quad \vdots \\ &P_{ik}^{\min} \le P_{ik} \le P_{ik}^{\max} \quad for\ fuel\ k \end{aligned} \tag{5}$$

3. The Proposed Methods for ELD with Multiple Fuel Options

The Lagrange optimization function L is formulated as follows [3]:

$$L = \sum_{i=1}^{N} C_T(P_{ik}) - \lambda\ (\sum_{i=1}^{N} P_{ik} - P_D) \tag{6}$$

The dual variables are obtained by equating to zero the partial derivatives of the Lagrange with respect to the dependent variables yielding the following equations.

$$\frac{\partial L}{\partial P_{ik}} = \frac{\partial C_T(P_{ik})}{\partial P_{ik}} - \lambda = 0 \tag{7}$$

$$\frac{\partial L}{\partial \lambda} = \sum_{i=1}^{N} P_{ik} - P_D = 0 \tag{8}$$

From the eq. (7) above, two proposed methods are shown as below.

3.1. The First Proposed Method

The incremental cost is obtained using eq. (7) as below.

$$\lambda = a_{ik} P_{ik} + b_{ik} \tag{9}$$

The power output of the *ith* generating unit is determined by

$$P_{ik} = \frac{\lambda - b_{ik}}{a_{ik}} \tag{10}$$

The overall iterative procedure for solving the economic load dispatch by using the first proposed method is shown in Figure 1.

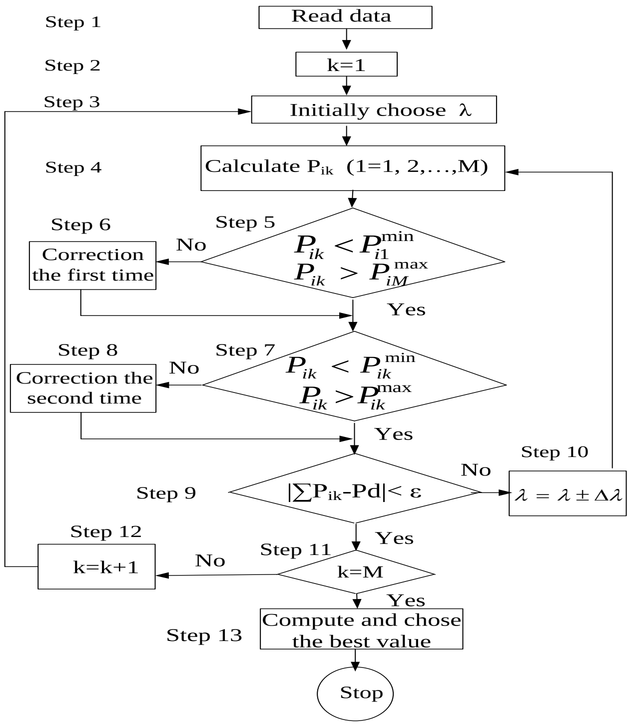

Figure 1. The Flow Chart for Solving ELD Problem Using the First Proposed Method

Explanation for correction at steps 6 and 8 is as below:

Step 6: Assign $P_{ik} = P_{i1}^{\min}$, if $P_{ik} < P_{i1}^{\min}$

or $P_{ik} = P_{iM}^{\max}$, if $P_{ik} > P_{iM}^{\max}$

Step 8: Assign:

$a_{ik} = a_{ik}-1$; $b_{ik} = b_{ik}-1$; $c_{ik} = c_{ik}-1$;

$P_{ik}^{\min} = P_{ik-1}^{\min}$; $P_{ik}^{\max} = P_{ik-1}^{\max}$, if $P_{ik} < P_{ik}^{\min}$

Or $a_{ik} = a_{ik}+1$; $b_{ik} = b_{ik}+1$; $c_{ik} = c_{ik}+1$

$P_{ik}^{\min} = P_{ik+1}^{\min}$; $P_{ik}^{\max} = P_{ik+1}^{\max}$, if $P_{ik} > P_{ik}^{\max}$

3.2. The Second Proposed Method

Based on equation (7), an equations series is obtained by

$$\left.\begin{aligned} a_{1k}P_{1k} + b_{1k} &= a_{2k}P_{2k} + b_{2k} \\ a_{1k}P_{1k} + b_{1k} &= a_{3k}P_{3k} + b_{3k} \\ &\vdots \\ a_{1k}P_{1k} + b_{1k} &= a_{Nk}P_{Nk} + b_{Nk} \end{aligned}\right\} \quad (11)$$

The power output of the *ith* generating unit is determined by

$$\left.\begin{aligned} P_{1k} &= \frac{a_{1k}}{a_{1k}}P_{1k} + \frac{b_{1k} - b_{1k}}{a_{1k}} \\ P_{2k} &= \frac{a_{1k}}{a_{2k}}P_{1k} + \frac{b_{1k} - b_{2k}}{a_{2k}} \\ &\vdots \\ P_{Nk} &= \frac{a_{1k}}{a_{Nk}}P_{1k} + \frac{b_{1k} - b_{Nk}}{a_{Nk}} \end{aligned}\right\} \quad (12)$$

Using Equation (2) and (12), the generations are rewritten as follows.

$$P_{1k} = \frac{P_D - \sum_{i=1}^{N} B_{ik}}{\sum_{i=1}^{N} A_{ik}} \tag{13}$$

$$P_{ik} = A_{ik} P_{1k} + B_{ik} \tag{14}$$

where

$$A_{ik} = \frac{a_{1k}}{a_{ik}} \tag{15}$$

$$B_{ik} = \frac{b_{1k} - b_{ik}}{a_{ik}} \tag{16}$$

The whole iterative procedure for solving the economic load dispatch by using the second proposed method is presented in Figure 2.

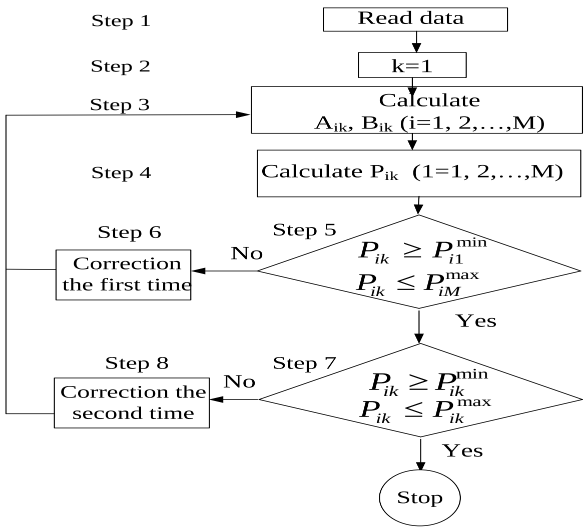

Figure 2. The Flow Chart for Solving ELD Problem Using the Second Proposed Method

Explanation for solving economic load dispatch problems:

Step 1: Read data

Step 2: Start with the first fuel type (k=1) for each generating unit.

Step 3: Calculate A_{ik}, B_{ik} using eqs (10).

Step 4: Calculate P_{ik} using eqs (8), (9).

Step 5: Check $P_{i1}^{min} \le P_{ik} \le P_{iM}^{max}$

If yes, go to step 7. Otherwise, go to step 6.

Step 6: If $P_{ik} < P_{i1}^{min}$, assign:

$a_{ik} = a_{i1}$; $b_{ik} = b_{i1}$; $c_{ik} = c_{i1}$

$P_{ik} = P_{i1}^{min}$

Step 7: If $P_{ik} > P_{iM}^{max}$, assign:

$a_{ik} = a_{iM}$; $b_{ik} = b_{iM}$; $c_{ik} = c_{iM}$

$P_{ik} = P_{iM}^{max}$

Then, back to step 3

Step 8: Check $P_{ik}^{min} \le P_{ik} \le P_{ik}^{max}$

If yes, the iterative process is terminated. Otherwise, go to step 8.

Step 1: If $P_{ik} < P_{ik}^{min}$, assign:

$a_{ik} = a_{ik}$-1; $b_{ik} = b_{ik}$-1; $c_{ik} = c_{ik}$-1

$P_{ik}^{min} = P_{ik-1}^{min}$; $P_{ik}^{max} = P_{ik-1}^{max}$

If $P_{ik} > P_{ik}^{max}$, assign:

$a_{ik} = a_{ik}$+1; $b_{ik} = b_{ik}$+1; $c_{ik} = c_{ik}$+1

$P_{ik}^{min} = P_{ik+1}^{min}$; $P_{ik}^{max} = P_{ik+1}^{max}$

Then, back to step 3.

4. Case Studies

The proposed methods have been implemented in Mat lab 7.2 programming language and executed on Intel(R) Core (TM)2 Duo CPU T7250 @2.00GHZ (2CPU) laptop. The maximum difference between load demand and power generated from the set of available units is set to 10^{-4}.

The test system consists of 10 generating units, each with two or three piecewise quadratic cost functions representing different fuel types. Total demands are gradually changed from 2,400 MW to 2,700 MW in steps of 100 MW with power loss neglected. The results of the proposed approach are compared to those from [33-39] for various load demands of 2,400 MW, 2,500 MW, 2,600 MW, and 2,700 MW.

The obtained results from the two proposed methods compared to those from others are respectively given in from Tables 1 to 4 corresponding to load demand of 2400 to 2700 MW. Obviously, the second proposed method is more effective and robust than the first proposed one once it converges to the optimal solution with faster computational time for all study cases and better cost for the last case of 2700 MW load.

The comparisons for all load demand cases have revealed that the HM and HNN obtain the worst solution quality and HNN is the slowest algorithm for getting convergence. In fact, the HNN spends 60 seconds converging to optimal solution whereas other methods are just run around several seconds. In addition to obtaining high total fuel cost, the two methods violate the load balance constraints for all cases. HM in [33] tends to generate more power that that required from system whereas total power generated from HNN in [34] is less than system requirement. On the contrary, EALHN in [39] is the best technique as it gets good solution and very short computational time. In spite of the advantages, EALHN also suffers the difficult task for determining a set of control parameters. On the other hand, the EALHN may get local optimal solution if the best parameters during selection process are missed. For all cases, the second proposed method shows its high performance due to high solution quality and short computational time obtained. Besides, it is nearly faster than other methods except EALHN [39] whereas the first proposed method converges to the local optimization for the last case because of its highest total cost. The best solutions for the two methods are respectively indicated in Tables 5 and 6.

Table 1. Comparison of Fuel Cost and CPU Time for Load Demand of 2,400 MW

Method	Total power	Cost ($/h)	CPU time (s)
HM [33]	2,401.2	488.50	1.08
HNN [34]	2,399.8	487.87	~60
AHNN [35]	2,400	481.72	~4
IEP [36]	2,400	481.779	-
MPSO [37]	2,400	481.723	-
EALHN [39]	2,400	481.723	0.008
Proposed method 1	**2400.0**	**481.7227**	**2.67**
Proposed method 2	**2400.0**	**481.7227**	**0.060**

Table 2. Comparison of Fuel Cost and CPU Time for Load Demand of 2,500 MW

Method	Total power	Cost ($/h)	CPU time (s)
HM [33]	2,500.1	526.70	-
HNN [34]	2,499.8	526.13	~60
AHNN [35]	2,500	526.230	~4
IEP [36]	2,500	526.304	-
MPSO [37]	2,500	526.239	6.1
CEP [38]	2,500	526.246	0.495
FEP [38]	2,500	526.262	0.394
IFEP [38]	2,500	526.246	0.558
EALHN [39]	2,500	526.239	0.006
Proposed method 1	**2500**	**526.239**	**4.7**
Proposed method 2	**2500**	**526.239**	**0.058**

Table 3. Comparison of Fuel Cost and CPU Time for Load Demand of 2,600 MW

Method	Total power	Cost ($/h)	CPU time (s)
HM [33]	2,599.3	574.03	-
HNN [34]	2,599.8	574.26	~60
AHNN [35]	2,600	574.37	~4
IEP [36]	2,600	574.473	-
MPSO [37]	2,600	574.381	-
EALHN [39]	2,600	574.381	0.005
Proposed method 1	**2600**	**574.380**	**4.69**
Proposed method 2	**2600**	**574.380**	**0.058**

Table 4. Comparison of Fuel Cost and CPU Time for Load Demand of 2,700 MW

Method	Total power	Cost ($/h)	CPU time (s)
HM [33]	2,702.2	625.18	-
HNN [34]	2,699.7	626.12	~60
AHNN [35]	2,700	626.24	~4
IEP [36]	2,700	623.851	-
MPSO [37]	2,700	623.809	-
EALHN [39]	2,700	623.809	0.013
Proposed method 1	**2700.005**	**626.257**	**3.39**
Proposed method 2	**2700**	**623.8092**	**0.05**

Table 5. Optimal Solution Obtained by the First Proposed Method

Unit	P_D=2400 MW		P_D=2500 MW		P_D=2600 MW		P_D=2700 MW	
	Fuel type	Gen	Fuel type	Gen	Fuel type	Gen	Fuel type	Gen
1	1	189.7406	2	206.5193	2	216.5441	2	226.5699
2	1	202.3428	1	206.4574	1	210.9057	1	215.3544
3	1	253.8953	1	265.7395	1	278.5439	1	291.3497
4	3	233.0456	3	235.9532	3	239.0966	3	242.2404
5	1	241.8297	1	258.0183	1	275.5192	1	293.022
6	3	233.0456	3	235.9532	3	239.0966	3	242.2404
7	1	253.2751	1	268.864	1	285.7168	1	302.5714
8	3	233.0456	3	235.9532	3	239.0966	3	242.2404
9	1	320.3832	1	331.4881	1	343.4932	3	355.4997
10	1	239.397	1	255.0567	1	271.9859	1	288.917
Total power (MW)	**2400**		**2500**		**2600**		**2700**	

Table 6. Optimal Solution Obtained by the Second Proposed Method

Unit	P_D=2400 MW		P_D=2500 MW		P_D=2600 MW		P_D=2700 MW	
	Fuel type	Gen	Fuel type	Gen	Fuel type	Gen	Fuel type	Gen
1	1	189.7405	2	206.5190	2	216.5442	2	218.2527

2	1	202.3427	1	206.4573	1	210.9058	1	211.6691
3	1	253.8953	1	265.7391	1	278.5441	1	280.6653
4	3	233.0456	3	235.9531	3	239.0967	3	239.6167
5	1	241.8297	1	258.0177	1	275.5194	1	278.5361
6	3	233.0456	3	235.9531	3	239.0967	3	239.6299
7	1	253.2750	1	268.8635	1	285.7170	1	288.6616
8	3	233.0456	3	235.9531	3	239.0967	3	239.6352
9	1	320.3832	1	331.4877	1	343.4934	3	428.49
10	1	239.3969	1	255.0562	1	271.9861	1	274.8433
Total power (MW)	**2400**		**2500**		**2600**		**2700**	

5. Conclusions

The paper proposes two simple and efficient methods based on Lagrange optimization theory for solving the problem of economic load dispatch with multiple fuel options in which the generator cost functions are represented as piece-wise quadratic cost functions. The performance of the methods has been tested on one system with different cases and the obtained results from them are compared to those from other methods reported in the paper. The comparisons among all methods have shown that the second method is more efficient than the first one in terms of solution quality and convergence speed. In addition, the second one also obtains better results than most methods available in the paper. Therefore, it can be concluded that the two methods proposed in the paper especially the second one are very efficiently applied to economic load dispatch problem with multiple fuel option.

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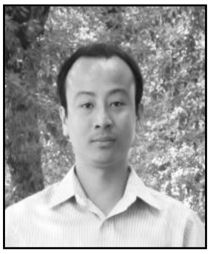

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