CHAPTER III

OPTIMAL ECONOMIC OPERATION OF POWER SYSTEMS

3.1 Introduction

The optimal economic operation of power systems or the economic dispatch (ED) problems is one of the most important optimization problems in power system operation. The main objective of the ED problem is to find the real power contribution from each generating unit of a system, so that the production costs are minimized for any specified load condition. The ED problem assumes that available generating units have been specified by a unit commitment study. In addition, it is assumed that the total system load has been estimated using a load-forecasting algorithm. In this chapter, we will consider the optimal economic operation of thermal generating units only.

The production cost for a generating unit consists of fixed and variable costs. Fixed cost, for example, the capital costs of installing the unit, is not considered in the ED problem. The unit's variable production cost includes fuel, labor, supplies, and maintenance costs. Among these, fuel cost constitutes the main component. The unit's fuel costs are typically provided in the form of a fuel-cost function which specifies the cost of the fuel used ($/hr.) as a function of the unit's real power output (MW). Labor, supplies, and maintenance costs can be taken into account by assuming they are a fixed percentage of the fuel costs. However, for simplicity, it is often assumed that fuel costs are the only variable production costs that needed to be considered.

Typically, the fuel cost function of generating unit has been approximately represented by a single quadratic function where the valve-point effects [46], prohibited operating zones [47], and multiple fuels [48] are usually ignored, which may introduce the dispatching results far from the optimum solution. In some cases, the calculated dispatched power may not be practically occurred since it falls within the prohibited operating zones. Therefore, it would be better if the generator cost curve can reflect practical operating constraints. However, the increase of the embedded constraints on generating unit's cost function usually results in higher nonlinear, non-smooth and non-convex function where the classical or gradient based methods [4] may be fail to apply.

In economic dispatch (ED) problems considering each nonconvex characteristic, i.e. valve-point effects, prohibited operating zones, and multiple-fuel options, several methods have been proposed. For instances, dynamic programming (DP) [4], genetic algorithm (GA) [46], evolutionary programming (EP) [49], particle swarm optimization (PSO) technique with the SQP method (PSO-SQP) [50], and the modified particle swarm optimization (MPSO) [51] are applied to solve the ED problem with valve-point effects. In the ED problem with prohibited operating zones, lambda iterative dispatch [52-53], deterministic crowding genetic algorithm (DCGA) [46], improved fast evolutionary programming (IFEP) [54], and the integrating evolutionary programming (EP), tabu search (TS) and quadratic programming (QP) called the ETQ methods [55] are proposed, while others, such as a hierarchical method (HM) [48], Hopfield neural network approach (HNN) [56], adaptive Hopfield neural network approach (AHNN) [57], evolutionary programming (EP) [58], and improved evolutionary programming (IEP) [59] are used to solve multiple-fuel problems. For more realistic situation in the ED problems, C. L. Chiang [60] proposed the improved genetic algorithm with multiplier updating (IGA_MU) to solve the ED problems in which multiple fuels with valve-point effects were considered simultaneously. However, none of the works mentioned above takes account of all the nonconvex fuel-cost characteristics into a single framework.

The following section will describe general variations of fuel cost characteristics of thermal generating units. Then, the formulations of the ED problems based on different fuel cost characteristics are proposed. Finally, to show the effectiveness of the proposed algorithm, numerical results of five test cases of the proposed SADE_ALM in chapter 2 are presented and compared with other approaches including conventional differential evolution (DE) approach based on the same constraint handling techniques.

3.2 General Variations of Fuel-Cost Characteristics

Generally, the fuel-cost characteristic for thermal generating unit is simplified by using a smooth and convex curve [4], e.g. second order polynomial as shown in (3.1)

$$f_i\left(P_{G_i}\right) = a_i P_{G_i}^2 + b_i P_{G_i} + c_i \tag{3.1}$$

Figure 3.1 shows the fuel cost curve of a typical thermal generating unit. However, there are cases when utilities may find it more convenient to model their fuel-cost curves using functions other than indicated in Figure 3.1 (e.g. linear, cubic, reduced-cubic [with quadratic term omitted], piecewise linear, exponential or combinations of these). In addition, the presence of valve-points, prohibited operating zones, or multiple fuels makes it impossible or impractical to represent a fuel-cost characteristic by a simplified quadratic polynomial.

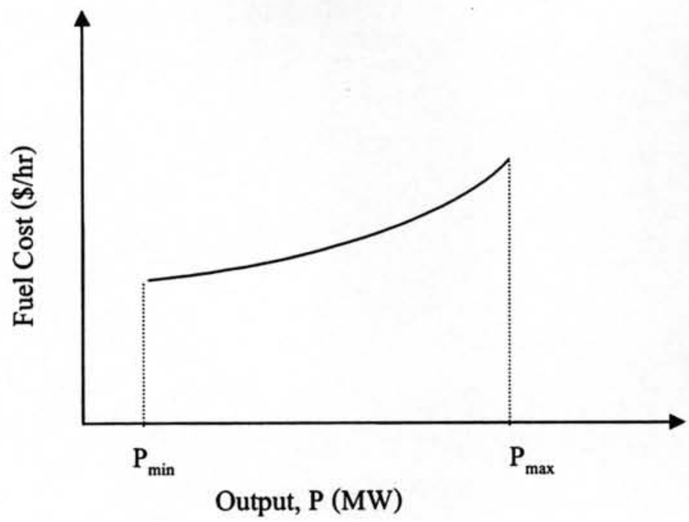


Figure 3.1 Fuel-cost curve of a thermal generating unit.

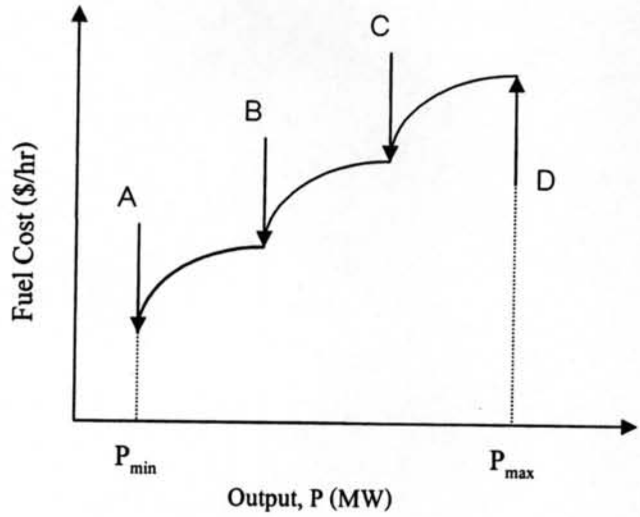
3.2.1 Valve-Point Effects

Usually, large thermal generating units have a number of steam admission valves, which are opened sequentially in order to obtain higher power output. Valve-points are those output levels at which a new admission valve is opened. Fig. 7 shows the fuel-cost curve for a thermal generating unit with four steam admission valves. Point A, B, C and D are the operating point of admission valves.

Whenever an admission valve starts to open, there is a sharp increase in throttling losses. As the valve is gradually lifted, these losses decrease until the valve is completely opened. The rippling effect seen in Figure 3.2 is the result of opening the steam admission valves. In [46] the effect of valve-points was modeled by adding a recurring rectified sinusoidal to the conventional quadratic cost curve resulting in the following fuel-cost function:

$$f_i(P_{G_i}) = a_i P_{G_i}^2 + b_i P_{G_i} + c_i + \left| d_i \times sin(e_i \times (P_{G_{i,min}} - P_{G_i})) \right| \qquad (3.2)$$

where a_i, b_i, c_i, are fuel cost functions of the unit i, and d_i, and e_i, are fuel cost coefficients of the unit with valve-point effects, and $P_{i,min}$ is the minimum generation of the unit in MW. Typically, valve-point effects are ignored in ED or OPF studies, due to the difficulty to handle by conventional optimization methods.



A, B, C, D: Operating points of admission valves

Figure 3.2 Fuel-cost curve of a thermal generating unit with four-steam admission valves.

3.2.2 Multiple Fuels

There are some thermal generating units which can be supplied by multiple fuel sources. In those cases, as shown in Figure 3.3, it is more appropriate to represent the unit's fuel-cost characteristic as a piecewise quadratic function [1, 2, 48]:

$$f_i(P_{G_i}) = \begin{cases} a_{i1}P_{G_i}^2 + b_{i1}P_{G_i} + c_{i1}, & fuel\ 1,\ P_{G_i}^{min} \le P_{G_i} \le P_{G_{i1}} \\ a_{i2}P_{G_i}^2 + b_{i2}P_{G_i} + c_{i2}, & fuel\ 2,\ P_{G_{i1}} \le P_{G_i} \le P_{G_{i2}} \\ \vdots & \vdots \\ a_{ik}P_{G_i}^2 + b_{ik}P_{G_i} + c_{ik}, & fuel\ k,\ P_{G_{i,k-1}} \le P_{G_i} \le P_{G_i}^{max} \end{cases} \tag{3.3}$$

where $a_{i,k}$, $b_{i,k}$, and $c_{i,k}$ are the cost coefficients of the unit at bus i for fuel type k.

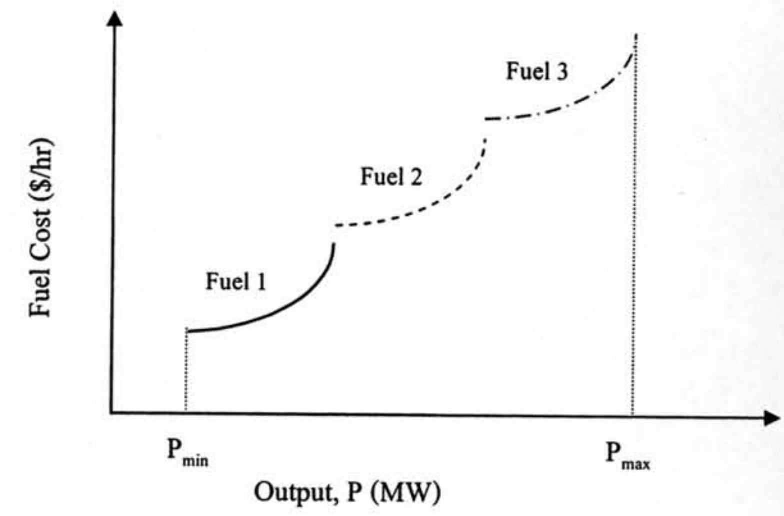


Figure 3.3 Fuel-cost curve of a thermal generating unit supplied with three fuels.

3.2.3 Prohibited Operating Zones

Generally, it is assumed that the output power of a thermal unit can be continuously adjusted over the unit's feasible operating region $(P_{gi}^{min} \leq P_{gi} \leq P_{gi,1}^{max})$. In practice, however, thermal units can have prohibited operating zones due to faults or physical operational limitations on power plant components. A unit with prohibited operating zones does not have a continuous fuel-cost curve, as shown in Figure 3.4.

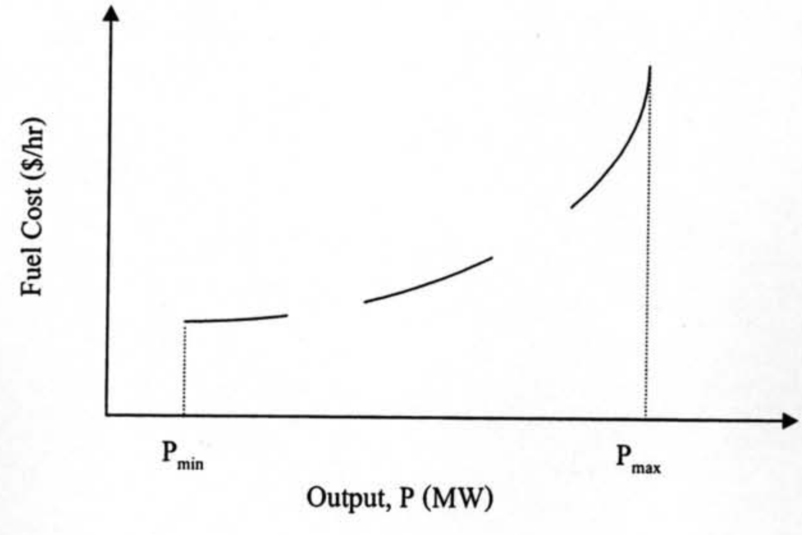


Figure 3.4 Fuel-cost curve of a thermal generating unit with two prohibited operating zones.

If the unit at bus i has n_i prohibited operating zones, then it has n_i+1 disjoint operating regions. The operating range for a unit with prohibited operating zones can be represented as [1, 2, 47]:

$$\begin{aligned} & P_{gi}^{min} \le P_{gi} \le P_{gi,1}^{L} \\ & P_{gi,k-1}^{U} \le P_{gi} \le P_{gi,k}^{L}, \quad k = 2,\dots,n_i \\ & P_{gi,n_i}^{U} \le P_{gi} \le P_{gi}^{max} \end{aligned} \tag{3.4}$$

where n_i is the number of prohibited operating zones for the unit at bus i, $P_{gi,k}^{L}$ is the lower bound of the k-th prohibited operating zone for the unit at bus i, and $P_{gi,k}^{U}$ is the upper-bound of the k-th prohibited operating zone for the unit at bus i.

3.3 Formulation of the ED Problems

In this section, we will describe the formulation of the ED problem based on different fuel cost characteristics. To consider the ED problem in more realistic situation, additional combined fuel cost characteristics are also considered in the ED problems, i.e. the fuel cost function considering multiple fuels with valve-point effects, and the fuel cost function considering multiple fuels, valve-point effects, and prohibited operating zones. The details of the formulation can be described as in the following.

3.3.1 ED Problem Considering Prohibited Operating Zones

The ED problem with some units possessing prohibited operating zones (POZ) can be mathematically stated as shown below [1, 2, 47].

$$Min \sum_{i \in \Omega} f_i(P_i) = Min \sum_{i \in \Omega} \left(a_i P_i^2 + b_i P_i + c_i \right) \tag{3.5}$$

where i : index of dispatchable units,

$f_i(\cdot)$: input-output cost function of unit i in \$/h,

P_i : generated power of unit i in MW,

a_i, b_i, c_i : cost coefficients of unit i,

Ω : a set of all dispatchable unit i, subject to the following constraints.

1) Power Balance Constraints:

$$\sum_{i \in \Omega} P_i = P_D + P_L \tag{3.6}$$

where P_D is the total load demand in MW, and P_L is the system power loss in MW.

2) System Spinning Reserve Constraints:

$$\sum_{i \in \Omega} S_i \geq S_R \tag{3.7}$$

$$S_i \geq Min\ \{(P_{i,max} - P_i),\ S_{i,max}\},\ \forall i \in (\Omega - \omega) \tag{3.8}$$

$$S_i = 0,\ \forall i \in \omega \tag{3.9}$$

where S_i : spinning reserve of unit i in MW,

S_R : system spinning reserve requirement in MW,

$P_{i,max}$: maximum generation of unit i in MW,

$S_{i,max}$: maximum spinning reserve of unit i in MW, and

ω : set of all dispatchable units with prohibited zones.

Since a unit with prohibited zones may operate into one of those zones while system load is regulating, it is shown in (3.9) that this kind of units should not contribute any regulating reserve to the system. In other words, system spinning reserve requirement must be satisfied by the units without prohibited operating zones.

3) Generating Limits of Units without Prohibited Zones:

$$P_{i,min} \leq P_i \leq P_{i,max},\ \forall i \in (\Omega - \omega) \tag{3.10}$$

where $P_{i,min}$ and $P_{i,max}$ are minimum and maximum generation of unit i in MW.

In order to manipulate the spinning reserve constraints, effective upper generation limit $P^{eff}_{i,\max}$ for each supplying unit i without prohibited zone is defined [52-53]. In this way, generating limits of those units will result in the following inequality constraint

$$P_{i,min} \leq P_i \leq P^{eff}_{i,max},\ \forall i \in (\Omega - \omega) \tag{3.11}$$

where $P^{eff}_{i,\max}$ is the effective upper generation limit of unit i in MW.

4) Generating Limits of Units with Prohibited Zones:

$$P_{i,min} \le P_i \le P_{i,1}^{l},\ or \\ P_{i,j-1}^{u} \le P_i \le P_{i,j}^{l},\ j = 2,\dots,Z_i,\ or \\ P_{i,Z_i}^{u} \le P_i \le P_{i,max},\ \forall i \in \omega \tag{3.12}$$

where $P_{i,j}^{l}$ and $P_{i,j}^{U}$ are the lower and the upper limits of the *j*th prohibited zones of unit *i* in MW, and Z_i is the number of prohibited zones of unit *i*.

3.3.2 ED Problem Considering Valve-Point Effects

A generator with multi-valve steam turbine has very different input-output cost function compared to the simple quadratic cost function in (3.1). To consider the valve-point effects in the cost model, the sinusoidal function is incorporated into the quadratic function as already shown in (3.2).

3.3.3 ED Problem Considering Multiple Fuels

Some generating units can operate under different fuel types. The use of multiple fuel types may result in multiple cost curves which are not necessarily parallel or continuous. The lower contour of the resulting cost curve determines the more economical fuel types to burn. The fuel cost function can be defined as already shown in (3.3).

3.3.4 ED Problem Considering Multiple Fuels with Valve-Point Effects

To obtain more practical ED problems, the fuel cost function should be incorporated both multiple fuels and valve-point effects simultaneously [60]. Therefore, the cost function of (3.3) should be combined with (3.2) to result in (3.13) and (3.14).

$$f_i(P_i) = \begin{cases} f_{i1}(P_i),\ fuel\,1,\ P_{i,min} \le P_i \le P_{i,1} \\ f_{i2}(P_i),\ fuel\,2,\ P_{i,1} \le P_i \le P_{i,2} \\ \vdots \\ f_{ik}(P_i),\ fuel\,k,\ P_{i,k-1} \le P_i \le P_{i,max} \end{cases} \tag{3.13}$$

$$f_{ik}(P_i) = a_{ik}P_i^2 + b_{ik}P_i + c_{ik} + \left|d_{ik}\,sin\left(e_{ik}\left(P_{ik,min} - P_i\right)\right)\right| \tag{3.14}$$

where a_{ik}, b_{ik}, and c_{ik} are cost coefficients of unit i for fuel type k, and $P_{ik,min}$ is the minimum generation of unit i using fuel type k.

3.3.5 ED Problem Considering Multiple Fuels with Valve-Point Effects, and Prohibited Operating Zones

To increase the capability and accuracy of the ED problems, all the nonconvex characteristics of generating unit should be incorporated into a single framework. Therefore, the cost function of (3.13) and (3.14) should be combined with (3.12) for units possessing prohibited operating zones (POZ).

In the next section, the effectiveness of the proposed algorithm will be tested and compared with previous reports. To handle the power balance constraints in all the ED problems, a slack generator is arbitrarily selected as a dependent generator (P_d) and defined by:

$$P_d = P_D - P_L - \sum_{i=1, i \neq d}^{N} P_i \tag{3.15}$$

where P_d is constrained by its associated minimum and maximum generation limit, $P_{d,min} \leq P_d \leq P_{d,max}$, P_D is the total system demand, P_L is the system power loss which may be found by B-matrix loss coefficients, etc. Therefore, in this case the power balance constraint is transformed to two inequality constraints according to its boundary limits.

3.4 Numerical Results

The solution quality and the effectiveness of the proposed SADE_ALM are verified using five test cases, i.e. 1) 40-generation system with valve-point effects [49], 2) 15-generation system with prohibited operating zones [47], 3) 10-generation system with multiple fuels [48], 4) 10-generation system considering multiple fuels and valve-points effects [60], and 5) 10-generation system considering multiple fuels, valve-points effects and prohibited operating zones. The conventional DE using the same constraint handling, i.e. DE_ALM, is also developed. In addition, both algorithms are implemented to solve the ED problems using the same DE's strategy (i.e., DE/rand/1/bin), and compared with previous reports [16, 46-60], e.g. evolutionary programming [49], modified particle swarm optimization (MPSO) [51], improved genetic algorithm with multiplier updating (IGA_MU) [60] etc. For each case, 100 independent runs were conducted. The population size NP is set at 5 for both DE_ALM and SADE_ALM. In addition, in case study 1, the result of NP=20 is also reported. The convergence tolerance ($\varepsilon_{\Delta X}$) and the *SVC* tolerance (ε_{SVC}) are set at 10^{-3} and 10^{-7} respectively, and the initial lagrange multiplier (β_k) of inequality constraints are set to zeros for all cases. The rest of the parameters will be shown later in each case. Both algorithms were implemented on free numerical software SCILAB 4.0 [61] on a PC Intel Celeron 2.40 GHz 256 MB of RAM.

3.4.1 Case 3.1: Valve-Point Effects

The first case study consists of forty generating units supplying load demand 10,500 MW. Only valve-point effects are considered. The cost function of each unit can be formulated as represented by (3.2). The system data and related constraints are available in Table B.1 [49]. The parameters of DE_ALM and SADE_ALM are selected as follows, i.e. 1) DE_ALM: NP = 5 and 20 where F = 0.7, CR = 0.7, r_g = 1e4, c_g = 5, r_{gmax} = 1e8, N_i = 5000, N_o = 20, and 2) SADE_ALM: NP = 5 and 20 where F = [0.2, 1], CR = [0.1, 1], r_g = 1e4, c_g = 5, r_{gmax} = 1e8, N_i = 5000, N_o = 20.

The results from both methods are compared with three EP based methods [49], i.e. FEP: fast EP, MFEP: FEP using the weighted mean of Gaussian and Cauchy mutations, IFEP: improved fast EP, MPSO: modified particle swarm optimization [51], and DEC-SQP: combining of differential evolution with sequential quadratic programming [16]. The comparisons are shown in Table 3.1. It can be found that, if we consider only the dispatching cost, the proposed SADE_ALM will provide the lowest cost. It demonstrates that the proposed algorithm is capable of searching for better solutions than other methods. It is also found that DE_ALM with NP = 20 can find a lower dispatching cost than FEP, MFEP, IFEP, MPSO, and DEC-SQP. Additionally, the proposed SADE_ALM can provide better dispatching cost and lower mean computation time than others.

Table 3.1 Result comparison for case 3.1

Methods	NP	Mean time (s)	Best time (s)	Mean cost ($)	Maximum cost ($)	Minimum cost ($)
FEP [49]	60	1039.16	1037.9	124119.37	127245.59	122679.71
MFEP [49]	60	2196.1	2194.7	123489.74	124356.47	122647.57
IFEP [49]	60	1167.35	1165.7	123382	125740.63	122624.35
MPSO [51]	20	N/A	N/A	N/A	N/A	122252.27
DEC-SQP [16]	30	N/A	N/A	122242.84	122839.29	121741.98
DE_ALM	5	110.98	14.08	125366.84	138101.14	122299.910
	20	345.491	307.578	121614.91	122059.27	121463.12
SADE_ALM	5	207.428	19.203	122572.23	125299.72	121535.84
	20	369.835	145.766	121523.91	121894.18	121435.72

Note: Based on different computing hardware

The best solution of DE_ALM and SADE_ALM are provided and compared with MPSO, and DEC-SQP in Table 3.2, where TP, TC, and CT are the total power (MW), total cost ($), and computation time (s). It should be reminded that various CT of the referred works shown in this paper may be obtained from different hardware specifications.

Table 3.2 The best result comparison for case 3.1

Unit (MW)	Methods					
	NP=30	NP = 20			NP = 5	
	DEC-SQP [16]	MPSO [51]	DE_ALM	SADE_ALM	DE_ALM	SADE_ALM
G1	111.7576	114	110.7998	113.6992	114.0000	113.8886
G2	111.5584	114	110.7998	114.0000	114.0000	114.0000
G3	97.3999	120	97.3999	97.5109	120.0000	120.0000
G4	179.7331	182.222	179.7331	179.7519	179.7331	179.7331
G5	91.6560	97	87.8000	88.9365	97.0000	93.0681
G6	140.0000	140	140.0000	140.0000	140.0000	140.0000
G7	300.0000	300	300.0000	259.6802	300.0000	300.0000
G8	300.0000	299.021	284.5997	284.5979	300.0000	284.5898
G9	284.5997	300	284.5997	284.7278	300.0000	284.6004
G10	130.0000	130	130.0000	130.0001	130.0000	130.0328
G11	168.7998	94	94.0000	168.8295	168.7998	168.7998
G12	94.0000	94	94.0000	94.0000	94.0000	94.0000
G13	214.7598	125	214.6496	214.3887	125.0000	125.0000
G14	394.2794	304.485	304.5196	304.5567	304.5196	394.2802
G15	304.5196	394.607	394.2794	394.2784	304.5196	394.2799
G16	304.5196	305.323	394.2794	394.2737	304.5196	394.2793
G17	489.2794	490.272	489.2794	489.2955	489.2794	489.4716
G18	489.2794	500	489.2794	489.2790	500.0000	492.5760
G19	511.2794	511.404	511.2794	511.3253	511.2795	511.2997
G20	511.2794	512.174	511.2794	511.3204	511.2794	511.2795
G21	523.2794	550	523.2794	523.3047	530.5111	523.2838
G22	523.2853	523.655	523.2794	523.3838	550.0000	523.2796
G23	523.2847	534.661	523.2794	523.2952	550.0000	523.2799
G24	523.2794	550	523.2794	523.3464	550.0000	524.4939
G25	523.2794	525.057	523.2794	523.2965	523.2796	523.2982
G26	523.2794	549.155	523.2794	523.2905	550.0000	523.2794
G27	10.0000	10	10.0000	10.0065	10.0000	10.0000
G28	10.0000	10	10.0000	10.0017	10.0000	10.0000
G29	10.0000	10	10.0000	10.0000	10.0000	10.0000
G30	90.3329	97	96.4669	88.5979	97.0000	87.8004
G31	190.0000	190	190.0000	190.0000	190.0000	190.0000
G32	190.0000	190	190.0000	190.0000	190.0000	189.9998
G33	190.0000	190	190.0000	190.0000	190.0000	189.9999
G34	200.0000	200	200.0000	165.6929	200.0000	164.7918
G35	200.0000	200	200.0000	200.0000	200.0000	164.8022
G36	200.0000	200	200.0000	200.0000	200.0000	165.2330
G37	110.0000	110	110.0000	110.0000	110.0000	110.0000
G38	110.0000	110	110.0000	110.0000	110.0000	110.0000
G39	110.0000	110	110.0000	109.9903	110.0000	110.0000
G40	511.2794	512.964	511.2794	511.3420	511.2794	511.2794
TP (MW)	10500	10500	10500	10500	10500.0000	10500.0000
TC ($)	121741.9793	122252.27	121463.120	121435.720	122299.910	121535.840
CT (s)	N/A	N/A	309.344	324.547	225.084	503.531

Notes: 1) Based on different computing hardware

2) TP: total power (MW), TC: total cost ($), CT: computation time (s).

From Table 3.2, it can be seen that SADE_ALM requires more computation time than DE_ALM for both five and twenty population sizes, since the control variables of SADE_ALM are more than DE_ALM, due to *F* and *CR* are included into the chromosome. However, the total cost of SADE_ALM from both population size (5 and 20) are lower than DE_ALM, MPSO, and

DEC-SQP. It has been found that both SADE_ALM and DE_ALM methods can find the best solution once out of 100 initiated trials for both NP = 5 and 20. Figure 3.5 shows the convergence characteristic of SADE_ALM and DE_ALM for the case of NP=5. Figure 3.6 shows the convergence characteristic of inner loop iteration for the first outer loop of DE_ALM and SADE_ALM based on NP=5. The relative frequency of the solution convergence of SADE_ALM and other methods are listed in Table 3.3 for each cost range. It reveals that the proposed SADE_ALM can provide the global or quasi-global solution with a better probability than others.

Table 3.3 Relative frequency of the solution convergence for case 3.1

Methods	NP	Range of cost (k$)										
		138.5 - 127.0	127.0 - 126.5	126.5 - 126.0	126.0 - 125.5	125.5 - 125.0	125.0 - 124.5	124.5 - 124.0	124.0 - 123.5	123.5 - 123.0	123.0 - 122.5	122.5 - 120.0
CEP [49]	60	-	10	4	-	16	22	42	4	2	-	-
FEP [49]	60	-	6	-	4	2	10	20	26	24	6	-
MFEP [49]	60	-	-	-	-	-	-	14	26	50	10	-
IFEP [49]	60	-	-	-	2	-	4	4	18	50	22	-
MPSO [51]	20	-	-	-	-	-	-	-	-	-	53	47
DEC-SQP [16]	30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DE_ALM	5	10	5	8	6	10	10	12	27	9	2	1
	20	-	-	-	-	-	-	-	-	-	-	100
SADE_ALM	5	-	-	-	-	1	2	4	6	12	19	56
	20	-	-	-	-	-	-	-	-	-	-	100

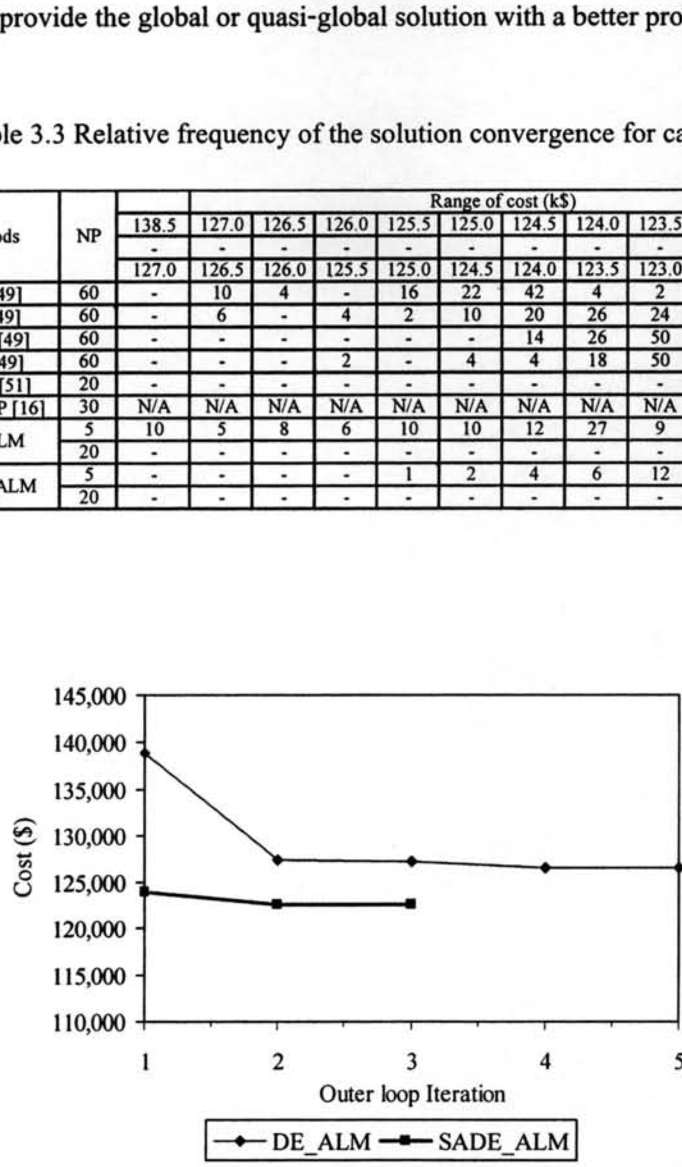


Figure 3.5 Convergence characteristic of DE_ALM and SADE_ALM for NP = 5.

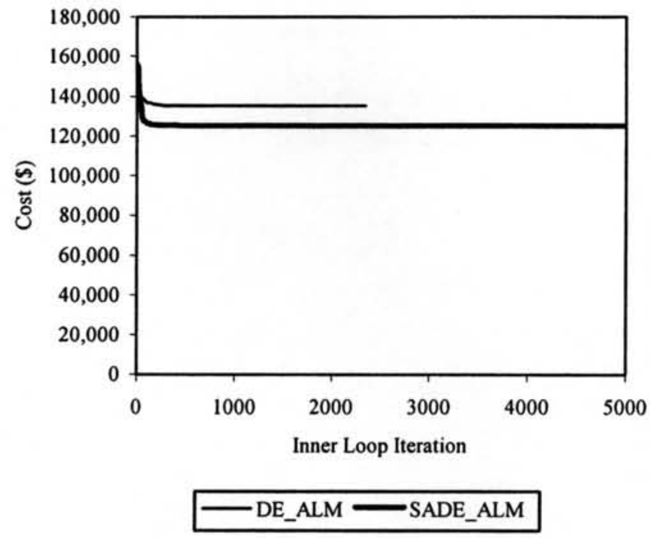


Figure 3.6 Illustration of inner loop convergence characteristic for the first outer loop of DE_ALM and SADE_ALM for NP = 5.

3.4.2 Case 3.2: Prohibited Operating Zones (POZ)

There are fifteen generating units considering only prohibited operating zone (POZ) in this case. Four of the units, no. 2, 5, 6, 12, occupy up to three prohibited operating zones (POZ). The total system demand is 2650 MW. The POZ constraints create 192 decision subspaces for the dispatching problem. System spinning reserve, S_R, is defined at 200 MW. All the system data and related constraints of this example are given in Table B. 2 and B. 3 [47]. The parameters for both DE_ALM and SADE_ALM are given as follows: 1) DE_ALM: NP = 5, F = 0.7, CR = 0.7, r_g = 1e5, c_g = 5, r_{gmax} = 1e8, N_i = 5000, N_o = 20, and 2) SADE_ALM: NP = 5, F = [0.2, 1], CR = [0.1, 1], r_g = 1e5, c_g = 5, r_{gmax} = 1e8, N_i = 5000, N_o = 20.

Table 3.4 shows the results of the proposed SADE_ALM with respect to the lambda iterative method, dynamic programming (DP), and deterministic crowding genetic algorithm (DCGA) presented in [47], improved fast evolutionary programming (IFEP) [54], fast evolutionary programming (FEP) [54], and the ETQ methods [55]. Both of the proposed SADE_ALM and the DE_ALM can provide not only better solution quality, but also completely satisfy the system constraints except for the DP which provides the same total cost. However, the DP is generally suffered from its dimensionality problem, and therefore, may not be practical to apply in real situation. Furthermore, it can be noticed from Table 3.4 that some solutions in the previous reports are infeasible. For instance, the lambda iterative method provides an infeasible solution due to unit 5 operating in the second prohibited zone [260 MW, 335 MW], while both IFEP [54] and FEP [54] also provide infeasible solutions due to the violation of the minimum generation of unit 7 and the maximum generation of unit 15 as described at the footnote of Table 3.4. Again, the computation time of SADE_ALM is larger than DE_ALM as in case 3.1. In addition, the number of the best solution found of SADE_ALM and DE_ALM are 2 and 6 out of the 100 randomly initiated trials respectively. However, both methods provide the same dispatching solution.

Table 3.4 The best results comparison for case 3.2

Unit (MW)	Methods							
	lambda [47]	DP[47]	DCGA [47]	IFEP [54]	FEP [54]	ETQ [55]	DE_ALM	SADE_ALM
G1	455.0	455.0	406.1	455.000	449.787	450	450	455
G2	455.0	455.0	453.8	450.845	450.000	450	450	455
G3	130.0	130.0	130.0	130.000	129.999	130	130	130
G4	130.0	130.0	130.0	130.000	130.000	130	130	130
G5	295.30[3)]	260.0	355.0	259.791	335.000	335	335	260
G6	460.0	460.0	456.8	460.000	455.018	455	455	460
G7	465.0	465.0	459.8	15.002[2)]	15.00[2)]	465	465	465
G8	60.0	60.0	60.0	60.014	60.000	60	60	60
G9	25.0	25.0	26.6	25.008	25.000	25	25	25
G10	20.0	20.0	21.6	20.045	20.000	20	20	20
G11	43.4	60.0	36.2	62.109	20.185	20	20	60
G12	56.3	75.0	59.0	77.172	55.006	55	55	75
G13	25.0	25.0	25.0	25.000	25.000	25	25	25
G14	15.0	15.0	15.0	15.008	15.000	15	15	15
G15	15.0	15.0	15.0	465.00[1)]	465.00[1)]	15	15	15
TP (MW)	2650.0	2650.0	2649.9	2649.994	2649.995	2650	2650	2650
TC ($)	32503	32506	32515	32507.46	32507.55	32507.5	32506.139	32506.139
CT (s)	N/A	N/A	N/A	3.138	2.769	15.8	5.679	12.558
NP	-	-	200	60	60	30	5	5

Notes: 1) violate maximum generation limit (55 MW).

2) violate minimum generation limit (135 MW).

3) unit loading in the 2nd prohibited zone [260 MW, 335 MW].

4) Computation time is based on different computing hardware

3.4.3 Case Study 3.3: Multiple Fuels

This case study concerns economic dispatch of generators with multi-fuel options. The cost characteristic of the units is a piecewise quadratic cost function represented by (3.3). It is assumed that the system consists of ten on-line generating units, each with two or three fuel options, supplying 2700 MW demand. The system data and related constraints of this case are given in Table B.4 [3]. The parameters for both DE_ALM and SADE_ALM are set as in the following, i.e. 1) DE_ALM: $NP = 5$, $F = 0.7$, $CR = 0.7$, $r_g = 1e4$, $c_g = 1.5$, $r_{gmax} = 1e8$, $N_i = 5000$, $N_o = 20$, and 2) SADE_ALM: $NP = 5$, $F = [0.2, 1]$, $CR = [0.1, 1]$, $r_g = 1e4$, $c_g = 1.5$, $r_{gmax} = 1e8$, $N_i = 5000$, $N_o = 20$.

Results of the proposed SADE_ALM are compared with HM [48], HNN [56], AHNN [57], EP [58], IEP [59], MPSO [51], CGA_MU [60], and IGA_MU [60]. The results are compared in Table 3.5. It reveals that the SADE_ALM and the DE_ALM can provide lower production cost than others, except MPSO [51], which reports very similar solution. However, the population size of both SADE_ALM and DE_ALM are smaller than the MPSO. The computation time of the SADE_ALM in this case is lower than the DE_ALM, whereas the number of the best solution found are 15 and 35 out of the 100 randomly initiated trials respectively. Tables 3.6 and 3.7 show that the mean cost and relative frequency of the convergence of the SADE_ALM are a little better than the DE_ALM, while the mean time is vice versa.

Table 3.5 The best results comparison for case 3.3

Unit (MW)	Methods									
	HM [48]		HNN [56]		AHNN [57]		EP [58]		IEP [59]	
	FT	Gen	FT	Gen	FT	Gen	FT	Gen	FT	Gen
G1	2	218.4	2	224.5	2	228.2	2	225.2	2	219.5
G2	1	211.8	1	215.0	1	214.8	1	215.6	1	211.4
G3	1	281.0	3	291.8	1	291.7	1	291.8	1	279.7
G4	3	239.7	3	242.2	3	242.3	3	242.1	3	240.3
G5	1	279.0	1	293.3	1	293.3	1	293.7	1	276.5
G6	3	239.7	3	242.2	3	242.2	3	241.9	1	239.9
G7	1	289.0	1	303.1	1	302.3	1	301.6	1	289.0
G8	3	239.7	3	242.2	3	242.3	3	242.8	3	241.3
G9	3	429.2	1	335.7	1	354.2	1	356.6	3	425.1
G10	1	275.2	1	289.5	1	288.9	1	288.7	1	277.2
TP (MW)	2702.2		2699.7		2700.0		2700.0		2700.0	
TC ($)	625.18		626.12		626.24		626.26		623.851	
CT (s)	N/A		N/A		N/A		N/A		N/A	
NP	-		-		-		N/A		30	

Unit (MW)	Methods									
	MPSO [51]		CGA_MU [60]		IGA_MU [60]		DE_ALM		SADE_ALM	
	FT	Gen	FT	Gen	FT	Gen	FT	Gen	FT	Gen
G1	2	218.3	2	218.4572	2	218.1248	2	218.3006	2	218.3006
G2	1	211.7	1	211.5140	1	211.6826	1	211.6603	1	211.6603
G3	1	280.7	1	280.8987	1	280.8630	1	280.7293	1	280.7293
G4	3	239.6	3	239.6241	3	239.6533	3	239.6217	3	239.6217
G5	1	278.5	1	278.5036	1	278.6304	1	278.4279	1	278.4279
G6	3	239.6	3	239.6390	3	239.6140	3	239.7042	3	239.7042
G7	1	288.6	1	288.6201	1	288.5725	1	288.5707	1	288.5707
G8	3	239.6	3	239.6211	3	239.7057	3	239.6390	3	239.6390
G9	3	428.5	3	428.5760	3	428.4542	3	428.4935	3	428.4935
G10	1	274.9	1	274.5462	1	274.6995	1	274.8528	1	274.8528
TP (MW)	2700.0		2700.0000		2700.0000		2700.0000		2700.0000	
TC ($)	623.809		623.8095		623.8093		623.8091		623.8091	
CT (s)	N/A		19.42		5.27		12.238		6.57	
NP	30		30		5		5		5	

Note: Based on different computing hardware

Table 3.6 Results comparison for case 3.3

Methods	NP	Mean time (s)	Best time (s)	Mean cost ($)	Maximum cost ($)	Minimum cost ($)
DE_ALM	5	13.91	6.21	625.4571	676.2156	623.8091
SADE_ALM	5	14.33	2.05	624.1013	631.6015	623.8091

Table 3.7 Relative frequency of the solution convergence for case 3.3

Methods	Range of cost ($)										
	676.5 - 633.5	633.5 - 632.5	632.5 - 631.5	631.5 - 630.5	630.5 - 629.5	629.5 - 628.5	628.5 - 627.5	627.5 - 626.5	626.5 - 625.5	625.5 - 624.5	624.5 - 623.5
DE_ALM	1	-	-	-	3	2	10	1	9	11	63
SADE_ALM	-	-	1	-	-	-	1	1	1	6	90

3.4.4 Case Study 3.4: Multiple Fuels with Valve-Point Effects

This test system consists of ten generating units considering both multiple-fuel options and valve-point effects simultaneously. The demand is considered at 2700 MW. The system data and related constraints are given in Table B.5 [60]. The parameters of DE_ALM and SADE_ALM use the same setting as in case 3.3. The aim of this case is to demonstrate the effectiveness of the proposed SADE_ALM for a more complicated ED problem, of which both multiple fuels and valve-point effects are considered. Table 3.8 compares the best results of the SADE_ALM with CGA_MU [60], IGA_MU [60], and DE_ALM. It has been found that the proposed SADE_ALM provides the best total production cost, however with a little higher computation time compared to IGA_MU, and DE_ALM. Moreover, the numbers of the best solution found are found once out of the 100 randomly initiated trials for both algorithms. Table 3.9 shows the SADE_ALM can find the lowest mean cost compared to the others for 100 randomly initiated trials. The relative frequency of convergence for the proposed algorithm and the other methods are listed in Table 3.10, which reveals that the proposed SADE_ALM can provide the global or quasi-global solution with higher probability than the other methods.

Table 3.8 The best results comparison for case 3.4

Unit (MW)	Methods							
	CGA_MU [60]		IGA_MU [60]		DE_ALM		SADE_ALM	
	FT	Gen	FT	Gen	FT	Gen	FT	Gen
G1	2	222.0108	2	219.1261	2	218.5940	2	218.5940
G2	1	211.6352	1	211.1645	1	211.2166	1	211.4642
G3	1	283.9455	1	280.6572	1	278.6406	1	280.6571
G4	3	237.8052	3	238.4770	3	237.6239	3	239.2363
G5	1	280.4480	1	276.4179	1	279.9345	1	279.9345
G6	3	236.0330	3	240.4672	3	239.6381	3	239.3707
G7	1	292.0499	1	287.7399	1	290.0985	1	287.7275
G8	3	241.9708	3	240.7614	3	240.4456	3	239.7738
G9	3	424.2011	3	429.3370	3	428.0649	3	427.6664
G10	1	269.9005	1	275.8518	1	275.7432	1	275.5755
TP (MW)	2700.0000		2700.0000		2700.0000		2700.0000	
TC ($)	624.7193		624.5178		623.8716		623.8278	
CT (s)	26.17		7.25		12.375		17.032	
NP	30		5		5		5	

Note: Based on different computing hardware

Table 3.9 Results comparison for case 3.4

Methods	NP	Mean time (s)	Best time (s)	Mean cost ($)	Maximum cost ($)	Minimum cost ($)
CGA_MU [60]	5	26.64	25.65	627.6087	633.8652	624.7193
IGA_MU [60]	5	7.32	7.14	625.8692	630.8705	624.5178
DE_ALM	5	6.856	2.046	626.1298	642.7812	623.8716
SADE_ALM	5	10.884	2.406	624.7864	634.8313	623.8278

Note: Based on different computing hardware

Table 3.10 Relative frequency of the solution convergence for case 3.4

Methods	Range of cost ($)										
	676.5 - 633.5	633.5 - 632.5	632.5 - 631.5	631.5 - 630.5	630.5 - 629.5	629.5 - 628.5	628.5 - 627.5	627.5 - 626.5	626.5 - 625.5	625.5 - 624.5	624.5 - 623.5
CGA_MU [60]	1	-	2	3	7	10	21	31	20	5	-
IGA_MU [60]	-	-	-	1	-	2	2	11	45	39	-
DE_ALM	6	1	2	1	2	2	10	3	10	2	61
SADE_ALM	1	-	-	2	2	1	1	4	5	9	75

3.4.5 Case Study 3.5: Multiple Fuels Options with Valve-Point Effects and Prohibited Operating Zones

All the nonconvex characteristics, i.e. multiple fuels, valve-point effects and prohibited operating zones, are combined into one single framework for a very complicated ED problem in this case. The test system consists of ten generating units supplying the demand of 2700 MW. The system data and related constraints for multiple-fuels options with valve-point effect are the same as in case 3.4 where the prohibited zones constraints of some selected units are proposed and presented in Table 3.11. The concerned parameters defined for both DE_ALM and SADE_ALM are the same as in case study 3.3.

The purpose of this case is to demonstrate the effectiveness of the proposed SADE_ALM when all the nonconvex characteristics are considered simultaneously. Table 3.12 compares the best results of the proposed SADE_ALM with the DE_ALM. It can be found that the SADE_ALM provide not only better total production cost, but also lower computation time than the DE_ALM. The number of the best solution found for both algorithms are 1 out of the 100 randomly initiated trials. The mean total production cost of the SADE_ALM is lower than the DE_ALM; however, the mean computation time of the SADE_ALM is slightly higher than the DE_ALM as shown in Table 3.13. The relative frequencies of solution convergence for both methods are listed in Table 3.14 for each cost range obtained from 100 randomly initiated trials. It reveals that the proposed SADE_ALM can provide the global or quasi-global solution with higher probability than the DE_ALM. However, both methods are capable of solving the problems.

Table 3.11 Proposed prohibited operating zones for case 3.5

Unit	Zone 1 (MW)	Zone 2 (MW)	Zone 3 (MW)
G1	[140, 170]	[215, 235]	-
G3	[270, 290]	[350, 365]	[400, 430]
G5	[260, 280]	[355, 365]	[445, 465]
G8	[100, 115]	[150, 180]	[230, 250]

Table 3.12 The best results comparison for case 3.5

Unit (MW)	Methods			
	DE_ALM		SADE_ALM	
	FT	Gen	FT	Gen
G1	2	215.0000	2	214.4824
G2	1	213.6923	1	212.4543
G3	1	270.0000	1	290.0000
G4	3	240.7144	3	240.5784
G5	1	280.0000	1	280.0000
G6	3	239.5056	3	238.6988
G7	1	292.4695	1	287.8306
G8	3	229.9647	3	229.9647
G9	3	440.0000	3	430.1931
G10	1	278.6540	1	275.7976
TP (MW)	2700.0000		2700.0000	
TC ($)	624.7543		624.5925	
CT (s)	17.594		11.063	
NP	5		5	

Table 3.13 Results comparison for case 3.5

Methods	NP	Mean time (s)	Best time (s)	Mean cost ($)	Maximum cost ($)	Minimum cost ($)
DE_ALM	5	9.032	2.438	627.0854	655.2930	624.7543
SADE_ALM	5	10.027	2.266	625.8382	639.2923	624.5925

Table 3.14 Relative frequency of the solution convergence for case 3.5

Methods	Range of cost ($)									
	676.5 - 633.5	633.5 - 632.5	632.5 - 631.5	631.5 - 630.5	630.5 - 629.5	629.5 - 628.5	628.5 - 627.5	627.5 - 626.5	626.5 - 625.5	625.5 - 624.5
DE_ALM	7	-	-	3	3	10	5	7	12	53
SADE_ALM	2	-	-	2	1	4	1	8	12	70

3.5 Conclusion

From the above five test cases, it is clearly shown that the proposed SADE_ALM is more effective than other approaches in terms of the quality of the total production cost with acceptable computation time. The proposed SADE_ALM shows promising capability for solving highly complicated economic dispatch problems. In the next chapter, we will discuss the solution procedure of the optimal power flow (OPF) that have been used wildly in power system operation and planning using both sequential and parallel algorithm of SADE_ALM.