Unit Commitment Problem

ECE619 Project Final Report

Jiahui Guo

May 6 2013

Supervised by Dr. Kevin Tomsovic.

Acknowledgement of Sources

For all ideas taken from other sources (books, articles, internet), the source of the ideas is mentioned in the main text and fully referenced at the end of the report.

All material which is quoted essentially word-for-word from other sources is given in quotation marks and referenced.

Pictures and diagrams copied from the internet or other sources are labelled with a reference to the web page or book, article etc.

Contents

Chapter 1

Overall Problem Definition

1.1 Background

Unit Commitment(UC) schedules the on-and-off times of the generating units, and calculates the minimum cost hourly generation schedule while ensuring that start-up and shut-down rates, minimum up and minimum down times are considered.

The UC is important because it is not only a way to promote the system economy, but also for the following reasons: [1]

1) Start-up, shut-down and the dynamic considerations in restarting the modern generating facilities are much more complex and costier than they were for smaller, older units;

2) Growth in system size to the point where even small percentage gains have becomes economically very important;

3) Increase in variation between the peak and off-peak power demands;

4) System planning requires automated computerized schedulers to simulate the effect of unit selection methods on the choice of new generation;

5) Scheduling problem has grown out of the effective reach of the "earlier" techniques because of the large variaty in efficiencies and types of power sources.

1.2 Problem Definition

In current system operation center, day-ahead schedule(Unit Commitment) and real-time balancing (Optimal Power Flow) are considered separately. In

day-ahead schedule, ISOs schedule the startup and shutdown state and the power output of each generator for each time interval in order to minimize the overall cost over the next 24 hours. In real time schedule, ISOs re-adjust each generator's output to balance demand and generation. This study only focuses on day-ahead UC problem. In this project, a single bus system with 4 generators and one aggregated load is proposed. The constraints listed as following are added at different stages in order to solve the problem from simplicity to complexity.

1.3   Modeling in Unit Commitment

1.3.1   Nomenclature

k Index for unit.

t Index for hour.

N_h Total hour horizon scheduled.

N_g Number of generator units.

$P_k(t)$ Amount of electricity generated by generator k in time period t.

Fs_k Half of start-up cost plus shut down cost.

$D(t)$ Forecasted system demand at time t.

$P_{min,k}$ Lower limit of real power generation of unit k.

$P_{max,k}$ Upper limit of real power generation of unit k.

$R(t)$ Amount of spinning reserve at time t.

$Z_k(t)$ Binary variable to indicate if generator k is on in time period t.

a_k, b_k, c_k Quadratic energy cost coefficients of unit k.

1.3.2   Modeling

$$\min \sum_{t=1}^{N_h} \sum_{k=1}^{N_g} [a_k(t) + b_k P_k(t) + c_k P_k^2(t) + Fs_k(1 - Z_k(t-1))]Z_k(t) \quad (1.1)$$

s.t.

$$\sum_{k=1}^{N_g} P_k(t) = D(t) \tag{1.2}$$

$$P_{min,k}(t)Z_k(t) \leq P_k(t) \leq P_{max,k}(t)Z_k(t) \tag{1.3}$$

$$P_k(t) + R_k(t) - \sum_{k=1}^{N_g} P_{max,k}Z_k(t) \leq 0 \tag{1.4}$$

$$Z_k(t) \in \{0,1\} \tag{1.5}$$

$$\forall k = 1, 2, ..., N_g \tag{1.6}$$

$$\forall t = 1, 2, ..., N_h \tag{1.7}$$

Chapter 2

Solving the UC Problem

2.1 Approaches

To solve the UC problem, there are various methods, classified as classical, non-classical and hybrid model [2,3]. In this project, the following methods are utilized, the differences are the number of constraints considered when solving the UC problem.

1) Priority List

2) Dynamic Programming

3) Dynamic Programming + Priority List

4) Particle Swarm Optimization

2.1.1 Priority List

The priority list is created according to each unit parameters. In this project, priority list is based on fuel cost obtained from the average fuel cost of each unit operating at its maximum output power. The average full-load cost α is defined as the cost per unit of power \$MW when the unit is at its full capacity. It can be expressed as

$$\alpha_i = \frac{f_i(P_{max,i})}{P_{max,i}} + b_i + c_i P_{max,i} \tag{2.1}$$

The units are ranked by their α in ascending order. Thus, the priority list of units will be formulated based on the order of α_i, in which a unit with the lowest α_i will have the highest priority to be dispatched. [4]

2.1.2 Dynamic Programming

For the dynamic programming, it is a methodical procedure which systematically evaluates a large number of possible decisions in a multi-step problem. The convention dynamic programming takes all the states into account, for a N_g generation, N_h hours UC scheduling, the total path is $(2^{N_g} - 1)^{N_h}$. In this project, the forward approach is utilized, the recursive algorithm is used to compute the minimum cost in hour t with feasible state I, i.e.

$$F_{t,I} = \min[F(t,I) + S_c(t-1, L => t, I) + F_{tc}(t-1, I) \qquad (2.2)$$

Where $F_{tc}(t,I)$ is the cost from initial state to hour t state I, $S_c(t-1, L => t, I)$ is the transition cost from state $(t-1, L)$ to state (t, I), and $F(t, I)$ is the production cost for state (t, I).

2.1.3 Dynamic Programming + Priority List

Since the priority list can have to choose better feasible states, for the dynamic programming, it doesn't have to traverse all the states, but only the feasible states filtered by priority list. And this method could promote the performance of dynamic programming. [5]

2.1.4 Particle Swarm Optimization

PSO algorithm exploits a population of individuals(particles) to probe promising regions of search space, and each particle moves with an adaptable velocity within the regions of decision space and retains a memory of the best position it ever encountered. The best position ever attained by each particle of the swarm is communicated to all other particles. The PSO assumes that the swarm is manipulated by the equation:

$$V_i^t = \omega V_i^{t-1} + C_1 \cdot rand_1 \cdot (P_{bi}^{t-1} - X_i^{t-1}) + C_2 \cdot rand_2 \cdot (P_{gbi}^{t-1} - X_i^{t-1}) \quad (2.3)$$

where

- ω: The inertia weight

- C_1, C_2: The acceleration coefficients

- $rand_1, rand_2$: Separately generated uniformed distributed random numbers between 0 and 1

- X_i: The position of the particle

- V_i: The velocity of the ith dimension

And the X_i^t is updated based on the velocity, since the X_i^t should be a binary, a sigmoid function is applied to the velocity to produce a threshold, as follows:

$$rand() < sigmoid(V_i) \ ? \ 1 \ : \ 0 \qquad (2.4)$$

The fitness function takes the reserve into consideration, and associates a penalty with the unbalance, as shown below:

$$
\begin{aligned}
fitness(P_k(t)) \quad = \quad & \sum_{t=1}^{N_h}\{\sum_{k=1}^{N_g}[a_k(t) + b_k P_k(t) + c_k P_k^2(t) + Fs_k(1 - Z_k(t-1))]Z_k(t) \\
+ \quad & \lambda \cdot C \cdot ((D(t) + R(t) - \sum_{k=1}^{N_g} P_{max,k} Z_k)^2\} \qquad (2.5)
\end{aligned}
$$

where

- C: A flag which used to indicate whether the constraint is violated, if so, $C = 1$, otherwise, $C = 0$.

- λ: The penalty coefficient.

The parameters in PSO should be carefully tuned, e.g. if the inertia weight is large, it benefits global search, while it is small, it is good at local search. In this project, a self-adjust weight is used as shown in the following equation.

$$\omega = \omega_{max} - \frac{(\omega_{max} - \omega_{min}) \cdot iter}{MaxIter} \qquad (2.6)$$

Also, the larger C_1 may cause the particle converge to a local optimal, while larger C_2 may cause the particle converge to a global optimal. The detailed parameters are obtained from [6].

2.2 Data and Parameters

The Generation data and load data are obtained from [7], as shown in Table 2.1 and Table 2.2.

1) Generation Data

2) Load Data

Hour	P$_{load}$	Hour	P$_{load}$	Hour	P$_{load}$	Hour	P$_{load}$
1	480	2	530	3	600	4	540
5	400	6	280	7	290	8	500

Table 2.1: Load data

Generation. No.	P$_{max}$ (MW)	P$_{min}$ (MW)	Start Cost Cold($)	Initial State at time 0	Coef$_a$ $	Coef$_b$ $/MWh	Coef$_c$ $/MWh^2
1	80	25	350	-5	970	17.26	0.0031
2	250	60	400	8	700	16.60	0.0020
3	300	75	600	8	680	16.50	0.0021
4	60	20	500	-6	800	19.70	0.0039

Table 2.2: Generator data

Chapter 3

Results

The test system:

- 4 Generation

- 8 hour UC scheduling.

The detailed scheduling results from these algorithms are listed in below sections, respectively.

3.1   Priority List

```
Solving Using Priority List Method.
*********************************************************************

UNIT COMMITMENT DETAILS IN EACH HOUR.


HOUR:  1              Load:  480.0 MW          TotalCost: $9560.0
-------------------------------------------------------------------
UNITS           ON/OFF          GENERATION      MIN MW          MAX MW
  1                0               0.0            0.0             0.0
  2                1             233.7           60.0           250.0
  3                1             246.3           75.0           300.0
  4                0               0.0            0.0             0.0
-------------------------------------------------------------------
TOTAL:             2             480.0          135.0           550.0
```

```
HOUR:  2            Load:  530.0 MW           TotalCost: $19999.6
------------------------------------------------------------------
UNITS         ON/OFF         GENERATION      MIN MW         MAX MW
  1             0               0.0           0.0            0.0
  2             1             250.0          60.0          250.0
  3             1             280.0          75.0          300.0
  4             0               0.0           0.0            0.0
------------------------------------------------------------------
TOTAL:          2             530.0         135.0          550.0



HOUR:  3            Load:  600.0 MW           TotalCost: $32982.6
------------------------------------------------------------------
UNITS         ON/OFF         GENERATION      MIN MW         MAX MW
  1             1              68.3          25.0           80.0
  2             1             250.0          60.0          250.0
  3             1             281.7          75.0          300.0
  4             0               0.0           0.0            0.0
------------------------------------------------------------------
TOTAL:          3             600.0         160.0          630.0



HOUR:  4            Load:  540.0 MW           TotalCost: $43599.3
------------------------------------------------------------------
UNITS         ON/OFF         GENERATION      MIN MW         MAX MW
  1             0               0.0           0.0            0.0
  2             1             250.0          60.0          250.0
  3             1             290.0          75.0          300.0
  4             0               0.0           0.0            0.0
------------------------------------------------------------------
TOTAL:          2             540.0         135.0          550.0



HOUR:  5            Load:  400.0 MW           TotalCost: $51763.0
------------------------------------------------------------------
UNITS         ON/OFF         GENERATION      MIN MW         MAX MW
  1             0               0.0           0.0            0.0
  2             1             192.7          60.0          250.0
  3             1             207.3          75.0          300.0
  4             0               0.0           0.0            0.0
------------------------------------------------------------------
```

13

```
TOTAL:            2         400.0        135.0           550.0


HOUR:  6            Load:  280.0 MW          TotalCost: $57227.7
-----------------------------------------------------------------
UNITS          ON/OFF        GENERATION     MIN MW        MAX MW
  1              0              0.0           0.0           0.0
  2              0              0.0           0.0           0.0
  3              1            280.0          75.0         300.0
  4              0              0.0           0.0           0.0
-----------------------------------------------------------------
TOTAL:            1            280.0         75.0         300.0


HOUR:  7            Load:  290.0 MW          TotalCost: $62869.3
-----------------------------------------------------------------
UNITS          ON/OFF        GENERATION     MIN MW        MAX MW
  1              0              0.0           0.0           0.0
  2              0              0.0           0.0           0.0
  3              1            290.0          75.0         300.0
  4              0              0.0           0.0           0.0
-----------------------------------------------------------------
TOTAL:            1            290.0         75.0         300.0


HOUR:  8            Load:  500.0 MW          TotalCost: $73180.4
-----------------------------------------------------------------
UNITS          ON/OFF        GENERATION     MIN MW        MAX MW
  1              0              0.0           0.0           0.0
  2              1            243.9          60.0         250.0
  3              1            256.1          75.0         300.0
  4              0              0.0           0.0           0.0
-----------------------------------------------------------------
TOTAL:            2            500.0         135.0         550.0


*****************************************************************

 The Optimal Total Cost is $73180.3876.
 Elapsed time:     0.0193 sec.
```

3.2 Dynamic Programming

```
Solving Using Dynamic Programming.
**********************************************************************
Starting processing the UC in hour 1
Starting processing the UC in hour 2
Starting processing the UC in hour 3
Starting processing the UC in hour 4
Starting processing the UC in hour 5
Starting processing the UC in hour 6
Starting processing the UC in hour 7
Starting processing the UC in hour 8

Processing Done!
**********************************************************************

UNIT COMMITMENT DETAILS IN EACH HOUR.


HOUR:  1             Load:  480.0 MW          TotalCost: $9560.0
----------------------------------------------------------------
UNITS           ON/OFF          GENERATION      MIN MW          MAX MW
  1               0               0.0             0.0             0.0
  2               1             233.7            60.0           250.0
  3               1             246.3            75.0           300.0
  4               0               0.0             0.0             0.0
----------------------------------------------------------------
TOTAL:            2             480.0           135.0           550.0


HOUR:  2             Load:  530.0 MW          TotalCost: $19999.6
----------------------------------------------------------------
UNITS           ON/OFF          GENERATION      MIN MW          MAX MW
  1               0               0.0             0.0             0.0
  2               1             250.0            60.0           250.0
  3               1             280.0            75.0           300.0
  4               0               0.0             0.0             0.0
----------------------------------------------------------------
TOTAL:            2             530.0           135.0           550.0
```

```
HOUR:  3           Load:  600.0 MW          TotalCost: $32982.6
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW         MAX MW
  1              1              68.3           25.0           80.0
  2              1             250.0           60.0          250.0
  3              1             281.7           75.0          300.0
  4              0               0.0            0.0            0.0
-------------------------------------------------------------------
TOTAL:           3             600.0          160.0          630.0


HOUR:  4           Load:  540.0 MW          TotalCost: $43599.3
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW         MAX MW
  1              0               0.0            0.0            0.0
  2              1             250.0           60.0          250.0
  3              1             290.0           75.0          300.0
  4              0               0.0            0.0            0.0
-------------------------------------------------------------------
TOTAL:           2             540.0          135.0          550.0


HOUR:  5           Load:  400.0 MW          TotalCost: $51763.0
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW         MAX MW
  1              0               0.0            0.0            0.0
  2              1             192.7           60.0          250.0
  3              1             207.3           75.0          300.0
  4              0               0.0            0.0            0.0
-------------------------------------------------------------------
TOTAL:           2             400.0          135.0          550.0


HOUR:  6           Load:  280.0 MW          TotalCost: $57227.7
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW         MAX MW
  1              0               0.0            0.0            0.0
  2              0               0.0            0.0            0.0
  3              1             280.0           75.0          300.0
  4              0               0.0            0.0            0.0
-------------------------------------------------------------------
```

16

```
TOTAL:                1           280.0          75.0           300.0


HOUR:  7            Load:  290.0 MW         TotalCost: $62869.3
-----------------------------------------------------------------
UNITS           ON/OFF        GENERATION     MIN MW         MAX MW
  1               0              0.0           0.0            0.0
  2               0              0.0           0.0            0.0
  3               1            290.0          75.0          300.0
  4               0              0.0           0.0            0.0
-----------------------------------------------------------------
TOTAL:                1           290.0          75.0           300.0


HOUR:  8            Load:  500.0 MW         TotalCost: $73180.4
-----------------------------------------------------------------
UNITS           ON/OFF        GENERATION     MIN MW         MAX MW
  1               0              0.0           0.0            0.0
  2               1            243.9          60.0          250.0
  3               1            256.1          75.0          300.0
  4               0              0.0           0.0            0.0
-----------------------------------------------------------------
TOTAL:                2           500.0         135.0           550.0


*****************************************************************

 The Optimal Total Cost is $73180.3876.
 Elapsed time:      0.6517 sec.
```

3.3   Dynamic Programming + Priority List

```
Solving Using Dynamic Programming + Priority List Method.
************************************************************************
Starting processing the UC in hour 1
Starting processing the UC in hour 2
Starting processing the UC in hour 3
Starting processing the UC in hour 4
Starting processing the UC in hour 5
Starting processing the UC in hour 6
Starting processing the UC in hour 7
Starting processing the UC in hour 8

Processing Done!
************************************************************************

UNIT COMMITMENT DETAILS IN EACH HOUR.
```

HOUR: 1	Load: 480.0 MW			TotalCost: $9560.0
UNITS	ON/OFF	GENERATION	MIN MW	MAX MW
1	0	0.0	0.0	0.0
2	1	233.7	60.0	250.0
3	1	246.3	75.0	300.0
4	0	0.0	0.0	0.0
TOTAL:	2	480.0	135.0	550.0

HOUR: 2	Load: 530.0 MW			TotalCost: $19999.6
UNITS	ON/OFF	GENERATION	MIN MW	MAX MW
1	0	0.0	0.0	0.0
2	1	250.0	60.0	250.0
3	1	280.0	75.0	300.0
4	0	0.0	0.0	0.0
TOTAL:	2	530.0	135.0	550.0

```
HOUR:  3            Load:  600.0 MW           TotalCost: $32982.6
------------------------------------------------------------------
UNITS           ON/OFF       GENERATION     MIN MW          MAX MW
  1               1            68.3          25.0            80.0
  2               1           250.0          60.0           250.0
  3               1           281.7          75.0           300.0
  4               0             0.0           0.0             0.0
------------------------------------------------------------------
TOTAL:            3           600.0         160.0           630.0



HOUR:  4            Load:  540.0 MW           TotalCost: $43599.3
------------------------------------------------------------------
UNITS           ON/OFF       GENERATION     MIN MW          MAX MW
  1               0             0.0           0.0             0.0
  2               1           250.0          60.0           250.0
  3               1           290.0          75.0           300.0
  4               0             0.0           0.0             0.0
------------------------------------------------------------------
TOTAL:            2           540.0         135.0           550.0



HOUR:  5            Load:  400.0 MW           TotalCost: $51763.0
------------------------------------------------------------------
UNITS           ON/OFF       GENERATION     MIN MW          MAX MW
  1               0             0.0           0.0             0.0
  2               1           192.7          60.0           250.0
  3               1           207.3          75.0           300.0
  4               0             0.0           0.0             0.0
------------------------------------------------------------------
TOTAL:            2           400.0         135.0           550.0



HOUR:  6            Load:  280.0 MW           TotalCost: $57227.7
------------------------------------------------------------------
UNITS           ON/OFF       GENERATION     MIN MW          MAX MW
  1               0             0.0           0.0             0.0
  2               0             0.0           0.0             0.0
  3               1           280.0          75.0           300.0
  4               0             0.0           0.0             0.0
------------------------------------------------------------------
```

```
TOTAL:               1            280.0         75.0            300.0


HOUR:  7            Load:  290.0 MW         TotalCost: $62869.3
-------------------------------------------------------------------
UNITS           ON/OFF         GENERATION      MIN MW        MAX MW
  1                0              0.0            0.0            0.0
  2                0              0.0            0.0            0.0
  3                1            290.0           75.0          300.0
  4                0              0.0            0.0            0.0
-------------------------------------------------------------------
TOTAL:               1            290.0         75.0            300.0


HOUR:  8            Load:  500.0 MW         TotalCost: $73180.4
-------------------------------------------------------------------
UNITS           ON/OFF         GENERATION      MIN MW        MAX MW
  1                0              0.0            0.0            0.0
  2                1            243.9           60.0          250.0
  3                1            256.1           75.0          300.0
  4                0              0.0            0.0            0.0
-------------------------------------------------------------------
TOTAL:               2            500.0          135.0         550.0


*******************************************************************

 The Optimal Total Cost is $73180.3876.
 Elapsed time:     0.1860 sec.
```

No.	Cost_{min}	No.	Cost_{min}	No.	Cost_{min}	No.	Cost_{min}	No.	Cost_{min}
1	80623.92	2	77172.67	3	80296.38	4	77172.67	5	77802.07
6	77207.24	7	77172.67	8	77172.67	9	77511.09	10	77172.67

Table 3.1: PSO result
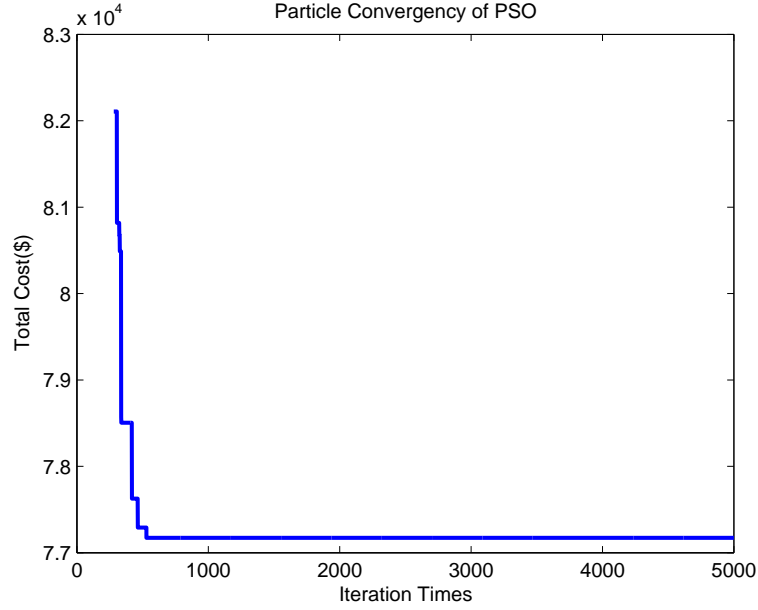
Figure 3.1: PSO fitness function iteration (1).

3.4 Particle Swarm Optimization

For the PSO, 10 times of execution are performed to obtain the best result, which are shown in Table 3.1.

Some figures showing the iteration process of the PSO fitness function are shown in Figure 3.1-3.3.
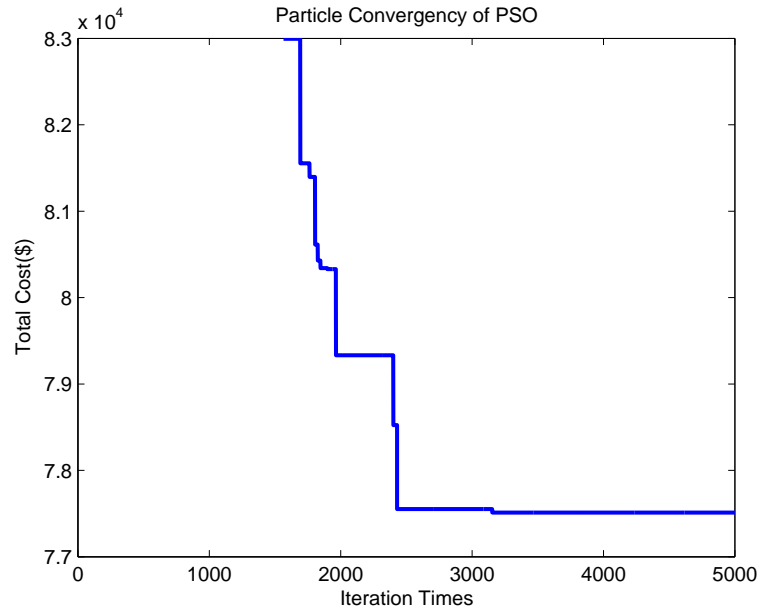
Figure 3.2: PSO fitness function iteration (1).
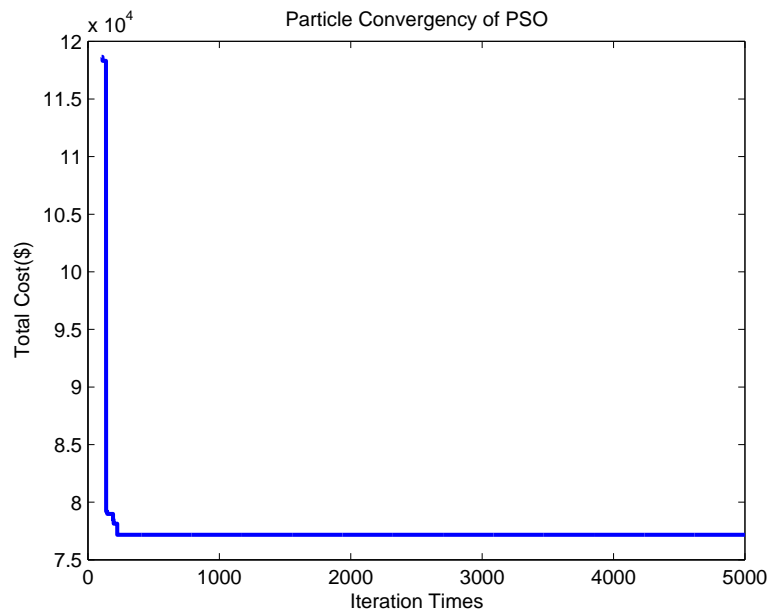
Figure 3.3: PSO fitness function iteration (3).

```
Solving Using Particle Swarm Optimization.
*********************************************************************

UNIT COMMITMENT DETAILS IN EACH HOUR.


HOUR:  1            Load:  480.0 MW         TotalCost: $10875.4
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW        MAX MW
  1              1             33.3           25.0          80.0
  2              1            216.6           60.0         250.0
  3              1            230.1           75.0         300.0
  4              0              0.0            0.0           0.0
-------------------------------------------------------------------
TOTAL:           3            480.0          160.0         630.0


HOUR:  2            Load:  530.0 MW         TotalCost: $22276.1
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW        MAX MW
  1              1             45.7           25.0          80.0
  2              1            235.9           60.0         250.0
  3              1            248.4           75.0         300.0
  4              0              0.0            0.0           0.0
-------------------------------------------------------------------
TOTAL:           3            530.0          160.0         630.0


HOUR:  3            Load:  600.0 MW         TotalCost: $34909.1
-------------------------------------------------------------------
UNITS          ON/OFF        GENERATION      MIN MW        MAX MW
  1              1             68.3           25.0          80.0
  2              1            250.0           60.0         250.0
  3              1            281.7           75.0         300.0
  4              0              0.0            0.0           0.0
-------------------------------------------------------------------
TOTAL:           3            600.0          160.0         630.0


HOUR:  4            Load:  540.0 MW         TotalCost: $46867.8
-------------------------------------------------------------------
```

23

```
UNITS          ON/OFF       GENERATION       MIN MW          MAX MW
  1              0             0.0             0.0             0.0
  2              1           250.0            60.0           250.0
  3              1           270.0            75.0           300.0
  4              1            20.0            20.0            60.0
-----------------------------------------------------------------------
TOTAL:           3           540.0           155.0           610.0


HOUR:  5           Load:  400.0 MW          TotalCost: $55031.5
-----------------------------------------------------------------------
UNITS          ON/OFF       GENERATION       MIN MW          MAX MW
  1              0             0.0             0.0             0.0
  2              1           192.7            60.0           250.0
  3              1           207.3            75.0           300.0
  4              0             0.0             0.0             0.0
-----------------------------------------------------------------------
TOTAL:           2           400.0           135.0           550.0


HOUR:  6           Load:  280.0 MW          TotalCost: $60496.2
-----------------------------------------------------------------------
UNITS          ON/OFF       GENERATION       MIN MW          MAX MW
  1              0             0.0             0.0             0.0
  2              0             0.0             0.0             0.0
  3              1           280.0            75.0           300.0
  4              0             0.0             0.0             0.0
-----------------------------------------------------------------------
TOTAL:           1           280.0            75.0           300.0


HOUR:  7           Load:  290.0 MW          TotalCost: $67161.6
-----------------------------------------------------------------------
UNITS          ON/OFF       GENERATION       MIN MW          MAX MW
  1              0             0.0             0.0             0.0
  2              1           136.3            60.0           250.0
  3              1           153.7            75.0           300.0
  4              0             0.0             0.0             0.0
-----------------------------------------------------------------------
TOTAL:           2           290.0           135.0           550.0
```

24

```
HOUR:  8              Load:  500.0 MW          TotalCost: $77072.7
--------------------------------------------------------------------
UNITS            ON/OFF          GENERATION      MIN MW          MAX MW
  1                0                0.0            0.0             0.0
  2                1              243.9           60.0           250.0
  3                1              256.1           75.0           300.0
  4                0                0.0            0.0             0.0
--------------------------------------------------------------------
TOTAL:             2              500.0          135.0           550.0


********************************************************************

 The Optimal Total Cost is $77172.6702.
 Elapsed time:   343.1562 sec.
```

Algorithm	Cost($)	Time(s)
PL	73180.39	0.0193
DP	73180.39	0.6517
DP+PL	73180.39	0.1860
PSO	77172.67	343.15

Table 3.2: Optimization result

3.5   The Optimization Result

The optimization result from these methods are shown in Table 3.2.

3.6   Observation

- The first three methods produce the same optimal solution, they all take the startup cost into consideration.

- Dynamic program needs more time than PL or DP+PL, since it needs to traverse more possible states.

- PSO considers the reserve constraint so that the optimal cost is higher than the other three.

3.7   The Running Time Comparison

The scale of the problem on time horizon is tested on $8h$, $16h$ and $24h$, it can be seen that the priority list, dynamic programming and their combination could produce almost linear runtime when the scheduling hour increase.
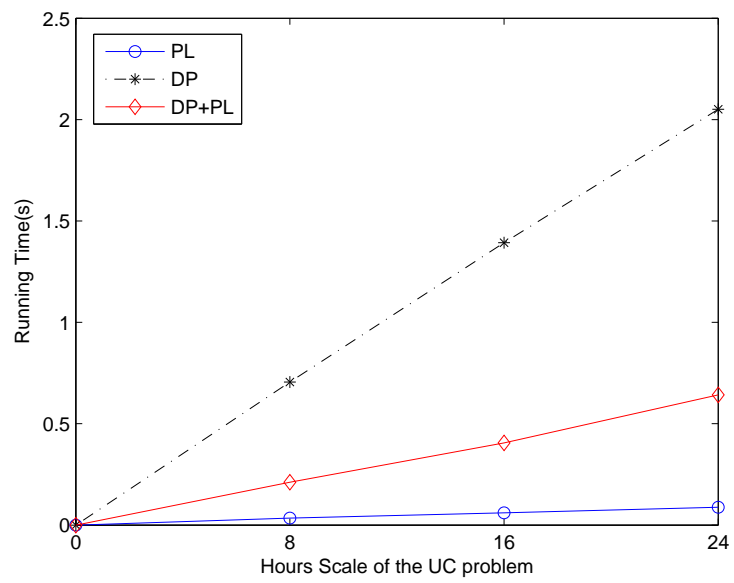
Figure 3.4: Running Time comparison between DP and PL.

Appendix A

Source Code

The hierarchy of the unit commitment solution code is shown as follows:

- UC.m

- GetData.m

  - PL

    * PriorityList.m

  - DP

    * PriorityList.m
    * FeasibleStates.m
    * Enumerate.m

  - PSO

    * PSO.m
    * fitness.m
    * sigmoid.m

- UnitTest.m

- ED.m

- PrintResult.m

A.1   Unit Commitment

```
function UC()
tic
```

```
global FULLSTATES;
global DEBUG;
format long;

% Unit Test for each function, 1 means printing each function result
DEBUG = 0;

% Obtain the generation data and load data
[genData,loadData] = GetData();

% Choose an algorithm to solve
Algorithm = 1;

% Algorithm used to solve the UC problem
% 1: Priority List(PL)
% 2: Dynamic Programming(DP) + Full states
% 3: Dynamic Programming(DP) + Priorty lists
% 4: Particle Swarm Optimization(PSO)

switch Algorithm
    case 1
        fprintf('\n\t\tSolving Using Priority List Method.');
        fprintf('\n%s \n',repmat('*',1,100'));
        % No startup cost considered when scheduling
        OptimalCost = PL(genData,loadData);
    case 2
        % Startup cost considered
        FULLSTATES = 1;
        fprintf('\n\t\tSolving Using Dynamic Programming.');
        fprintf('\n%s \n',repmat('*',1,100'));
        OptimalCost = DP(genData,loadData);
    case 3
        FULLSTATES = 0;
        fprintf('\n\t\tSolving Using Dynamic Programming + ...
                Priority List Method.');
        fprintf('\n%s \n',repmat('*',1,100'));
        OptimalCost = DP(genData,loadData);
        % Reserve requirement added
    case 4
        fprintf('\n\t\tSolving Using Particle Swarm Optimization.');
        fprintf('\n%s \n',repmat('*',1,100'));
```

```
        OptimalCost = PSO(genData,loadData);
    otherwise
        msgbox('Please specify a method!','WARNING!','warn');
end

t=toc;
fprintf('\n\n%s \n',repmat('*',1,100'));
fprintf('\n The Optimal Total Cost is $%10.4f.',OptimalCost);
fprintf('\n Elapsed time: %10.4f sec.\n\n',t)
```

A.2   Priority List

```
function [states, GMax, GMin] = PriorityList(G)
global DEBUG;

NG = length(G.Pmin);              % # of generation

% Generations are ranked based on their average fuel cost
% cheapest one comes first.
FAvgCost = G.Coef_a ./ G.Pmax + G.Coef_b + G.Coef_c .* G.Pmax;
[~,index] = sort(FAvgCost);

% Generate the priority list, each column stands for a state
% the latter column concludes one more cheapest generator
states = triu(ones(NG));
states(index,:) = states(1:NG,:);
states = logical(states);         % tranform to logical expression
GMax = cumsum(G.Pmax(index));
GMin = cumsum(G.Pmin(index));

if DEBUG
    % Unittest is performed to print out the result of this function
    UnitTest(1,states,GMax,GMin);
end


end
```

A.3   Dynamic Programming

```
function OptimalCost = DP(G, Load)
% Dynamic programming

global FULLSTATES;

% Calculate the size of unit commitment problem
Nh = length(Load);               % # of load hour

if FULLSTATES == 0
    % Using Priority-list
    [States,GMax,GMin] = PriorityList(G);
else
    % Enumerate all the combinations
    [States,GMax,GMin] = Enumerate(G);
end

% Save N = 1 lowest cost for each transition

% Determine the initial state
IniState = (G.IniState > 0);
[~,IniStateId] = ismember(IniState,States','rows');

% Captitalized HOUR and STATE are indices
for HOUR = 1 : Nh
    fprintf('Starting processing the UC in hour %d\n', HOUR);

    % record the status of previous hour
    if HOUR == 1
        PreStateId = IniStateId;      % initial state
        PreTransM  = PreStateId;
    else
        PreFCost   = CurFCost;
        PreStateId = CurTransM(:,end);
        PreTransM  = CurTransM;
    end

    % Find all the feasible states for each hour(states index)
    [FeasiState, flag] = FeasibleStates(Load,GMax,GMin,HOUR,States);
    if (~flag)
```

```
        return;
end

NF = length(FeasiState);              % # of feasible states
NP = length(PreStateId);              % # of previous states
% Initialize the parameters
% The total cost of getting to all feasible states in current hour
CurFCost  = zeros(NF,1);
% Transition matrix of optimal path to all feasible states in current hour
CurTransM = zeros(NF,HOUR+1);
% Total cost list for all previous states to a current state
TotalCost = zeros(NP,1);
% Search each feasible state
for CurStateCnt = 1 : NF
    CurState = States(:,FeasiState(CurStateCnt));
    % Search each previous feasible state
    for PreStateCnt = 1 : NP
        if HOUR == 1
            PreState = IniState';
        else
            PreState = States(:,PreStateId(PreStateCnt));
        end
        % Check the state transition
        % stateTrans = 1 means commited, =1 means decommited
        StateTrans = CurState - PreState;
        % The start cost is cosidered as cold start
        GenStartCost = (StateTrans > 0)'.* G.Fsc;
        % For each feasible state, calculate the cost and dispatch
        [~,Cost] = ED(G.Coef_a,G.Coef_b,G.Coef_c,G.Pmax,G.Pmin,...
                      Load(HOUR),States(:,FeasiState(CurStateCnt)));
        if HOUR == 1
            TotalCost(PreStateCnt) = Cost + sum(GenStartCost);
        else
            TotalCost(PreStateCnt) = Cost + sum(GenStartCost)...
                                     + PreFCost(PreStateCnt);
        end
    end

    % Calculate the minimum cost to get to current state
    [CurFCost(CurStateCnt), Index] = min(TotalCost);
    % Update the transition matrix
```

```
            CurTransM(CurStateCnt,1:size(PreTransM,2)) = PreTransM(Index,:);
            CurTransM(CurStateCnt,end) = FeasiState(CurStateCnt);
        end
end
% End of search all the combination, then find the best path
[OptimalCost,Index] = min(CurFCost);
BestPath = CurTransM(Index,:);

fprintf('\nProcessing Done!');
fprintf('\n%s \n',repmat('*',1,100'));
% Print the UC result
PrintResult(G,Load,States(:,BestPath));
end
```

A.4   Particle Swarm Optimization

```
function [OptimalCost,Pg] = PSO(G,Load)

% Setting the parameter for PSO
C1      = 2.02;          % Acceleration Coefficients
C2      = 2.05;
Xmin    = 0.0;           % Particle position limit
Xmax    = 1.0;
Wmin    = 0.2;           % The inertia weight limit
Wmax    = 1.0;
MaxIter = 5000;          % The maximum iteration times

% Solve the UC
NG = length(G.Pmin);     % # of generation
Nh = length(Load);       % # of load hour
X  = zeros(NG,Nh);       % The position of the particle(ON/OFF states)
V  = zeros(NG,Nh);       % Velocity of the i-th dimension
Pg = zeros(NG,Nh);       % Global best record
D  = 2^NG;               % Dimension of the search space

% The fitness objective
FITg = ones(MaxIter,1) * Inf;        % global best
FITp = ones(D,1) * Inf;              % personal best

% Define the swarm of the particle in the whole search space
```

```
S  = cell(2,D);                             % Current position
Pb = cell(1,D);                             % Personal best position

% Initialize the particles and velocity
for k = 1 : D
    for i = 1 : NG
        for j = 1 : Nh
            X(i,j) = randi([Xmin,Xmax]);        % random initialize position
            V(i,j) = Xmin + rand*(Xmax - Xmin); % random initialize velocity
        end
    end
    Pb{k}  = X;
    S{1,k} = X;
    S{2,k} = V;
end

% PSO iteration to search the global optimal objective
for iter = 1 : MaxIter
    w = Wmax - (Wmax - Wmin)*iter/MaxIter;      % inertial weight approach
    for k = 1 : D
        X = S{1,k};
        V = S{2,k};
        for i = 1 : NG
            for j = 1 : Nh
                % Update the velocity
                V(i,j) = w*V(i,j) + C1*rand*(Pb{k}(i,j)-X(i,j)) ...
                            + C2*rand*(Pg(i,j)-X(i,j));

                % Using sigmoid function as a threshold
                if(rand < sigmoid(V(i,j)))
                    X(i,j) = 1;
                else
                    X(i,j) = 0;
                end
            end
        end

        % Update the current particle
        S{1,k} = X;
        S{2,k} = V;
```

```matlab
        % Calculate the fitness for current particle
        FIT = fitness(G,Load,X);

        % Update the personal best position vector
        if FIT < FITp(k)
            FITp(k) = FIT;
            Pb{k} = X;
        end
    end

    % Update the global best position vector
    [FITg(iter), index] = min(FITp);
    Pg = Pb{index};
end

if FITg(iter) == Inf
    OptimalCost = Inf;
    fprintf('Not Converge!');
    %msgbox('PSO does not converge!','WARNING','warn');
    return;
end

% Plot the iteration of the optimal cost
figure;
plot(FITg,'LineWidth',2);
xlabel('Iteration Times');
ylabel('Total Cost($)');
title('Particle Convergency of PSO');

% Determine the initial state
IniState = (G.IniState > 0)';
States = [IniState,Pg];

% Print the scheduling result
PrintResult(G,Load,States);
OptimalCost = FITg(iter);

end
```

A.5 Economic Dispatch

```
function [P, Cost] = ED(a,b,c,GMax,GMin,Load,state)
global DEBUG;
warning off %#ok<WNOFF>

state = logical(state);                 % tranform to logical expression
% F(P) = a+b*P+c*P^2
NG = length(GMin);
P = zeros(NG,1);

lb = GMin(state);
ub = GMax(state);
H = 2*diag(c(state));
f = b(state);
Aeq = ones(1,NG);
Aeq = Aeq(state');
beq = Load;
options = optimset('Display','Off');
[Gen,Cost,exitflag] = quadprog(H,f,[],[],Aeq,beq,lb,ub,[],options);
if exitflag == 1
    Cost = Cost + a*state;
    P(state) = Gen;
else
    Cost = Inf;
    if DEBUG
        msg = ['No feasible dispatch for current combination: ', ...
                num2str(state'), '!'];
        msgbox(msg,'WARNING!','warn');
    end
    return;
end

end
```

A.6 Get Data

```
function [G, L] = GetData()

L = [480;530;600;540;400;280;290;500];
```

```
G.Pmin     = [25,60,75,20];                    %MW
G.Pmax     = [80,250,300,60];                   %MW
G.Fsc      = [350,400,600,500];                 %Cold startup cost
G.Fsd      = [0,0,0,0];                          %Shut down cost
G.IniState= [-5,8,8,-6];                         %Init Condition

G.RampUp   = [50,80,100,80];                     %MW/h
G.RampDown= [75,120,150,120];                    %MW/h

G.Coef_a   = [970,700,680,800];                  %$
G.Coef_b   = [17.26,16.60,16.50,19.70];          %$/MWh
G.Coef_c   = [0.0031,0.0020,0.0021,0.0039];      %$/MWh^2
end
```

A.7   Generate All the States

```
function [states,GMax,GMin] = Enumerate(G)
global DEBUG;

NG = length(G.Pmin);            % # of generation

% Generate the full states list, each column stands for a state
states = dec2bin(1:2^NG-1);
% tranform to logical expression
states = logical(sscanf(states,'%1d',size(states)));
GMax = states * G.Pmax';
GMin = states * G.Pmin';
states = states';

if DEBUG
    UnitTest(2,states,GMax,GMin);
end

end
```

A.8   Find Feasible States

```
function [NStates, flag] = FeasibleStates(Load,GMax,GMin,HOUR,states)
```

```
global DEBUG;

NStates = find(Load(HOUR) <= GMax & Load(HOUR) >= GMin);
if isempty(NStates)
    flag = false;
    msg = ['No feasible states in hour ', num2str(HOUR), '!'];
    msgbox(msg,'No feasible states!','warn');
    return;
else
    flag = true;

    if DEBUG
        UnitTest(3,states(:,NStates),GMax(NStates),GMin(NStates));
    end
end
end
```

A.9 Sigmoid Function

```
function y = sigmoid(x)
    y = 1/(1+exp(-x));
end
```

A.10 Unit Test

```
function UnitTest(varargin)

if varargin{1} == 1              % Unit test for priority list states
    states = varargin{2};
    GMax = varargin{3};
    GMin = varargin{4};
    printStates(states,GMax,GMin);

elseif varargin{1} == 2          % Unit test for enumerate states
    states = varargin{2};
    GMax = varargin{3};
    GMin = varargin{4};
    printStates(states,GMax,GMin);
```

```
elseif varargin{1} == 3          % Unit test for feasible states search
    states = varargin{2};
    GMax = varargin{3};
    GMin = varargin{4};
    printStates(states,GMax,GMin);
end

function printStates(states,GMax,GMin)
NG = size(states,1);
fprintf('   State No.       MW min        MW max                      Units\n');
fprintf('%s',repmat(' ',1,23));
fprintf(['                  ',repmat('    %5d ', 1, NG)],1:NG);
fprintf('\n %s \n',repmat('-',1,80'));
for i=1:size(states,2)
    fprintf('     %2d       %8.1f      %8.1f ',i,GMax(i),GMin(i));
    fprintf([repmat('       %2d ', 1, size(states,1)) '\n'], states(:,i));
end
fprintf('%s \n',repmat('-',1,80'));
end
```

A.11   Print Result

```
function OptimalCost = PrintResult(G,Load,FullStates)

NG = length(G.Pmin);             % # of generations
Nh = length(Load);               % # of load hour
TotalCost = zeros(Nh,1);
CurState  = zeros(NG,Nh);
% Print
fprintf('\n\t\tUNIT COMMITMENT DETAILS IN EACH HOUR.');
for HOUR = 1 : Nh
    CurState(:,HOUR) = FullStates(:,HOUR+1);
    % Check the state transition
    % stateTrans = 1 means commited, =1 means decommited
    StateTrans = CurState(:,HOUR) - FullStates(:,HOUR);
    % The start cost is cosidered as cold start
    GenStartCost = (StateTrans > 0)'.* G.Fsc;
    GMin = CurState(:,HOUR).* G.Pmin';
    GMax = CurState(:,HOUR).* G.Pmax';
    [Generation,Cost] = ED(G.Coef_a,G.Coef_b,G.Coef_c,G.Pmax,G.Pmin,...
```

```matlab
                              Load(HOUR),CurState(:,HOUR));
    if HOUR == 1
        TotalCost(HOUR) = Cost + sum(GenStartCost);
    else
        TotalCost(HOUR) = Cost + sum(GenStartCost) + TotalCost(HOUR-1);
    end
    S = ['UNITS             '
         'ON/OFF            '
         'GENERATION        '
         'MIN MW            '
         'MAX MW            '];
    TEMP = [(1:NG).',CurState(:,HOUR),Generation,GMin,GMax];
    fprintf('\n\n\nHOUR: %2d              Load:%7.1f MW            ...
            TotalCost: $%6.1f',HOUR,Load(HOUR),TotalCost(HOUR));
    fprintf('\n%s \n',repmat('-',1,100'))
    fprintf([repmat('%15s ', 1, size(S,1)) '\n\n'], S');fprintf('\n');
    fprintf(['%3d %15d ',repmat('%15.1f', 1, size(TEMP,2)-2) '\n'], TEMP.');
    fprintf('%s \n',repmat('-',1,100'));
    fprintf('TOTAL: %12d  %14.1f %14.1f %14.1f %14.1f %14.1f\n', ...
            sum(CurState(:,HOUR)),sum(Generation), sum(GMin), sum(GMax));
end
OptimalCost = TotalCost(end);
end
```

Bibliography

[1] J. A.Momoh, *Electric Power System Application of Optimization, Second Edition.* Boca Raton, FL: CRC Press, 2009.

[2] A. Bhardwaj, V. Kamboj, V. Shukla, B. Singh, and P. Khurana, "Unit commitment in electrical power system-a literature review," in *Power Engineering and Optimization Conference (PEDCO) Melaka, Malaysia, 2012 Ieee International*, 2012, pp. 275–280.

[3] N. Padhy, "Unit commitment problem under deregulated environment- a review," in *Power Engineering Society General Meeting, 2003, IEEE*, vol. 2, 2003, pp. –1094 Vol. 2.

[4] "An improved binary particle swarm optimization for unit commitment problem," *Expert Systems with Applications*, vol. 36, no. 4, pp. 8049 – 8055, 2009.

[5] T. Senjyu, K. Shimabukuro, K. Uezato, and T. Funabashi, "A fast technique for unit commitment problem by extended priority list," *Power Systems, IEEE Transactions on*, vol. 18, no. 2, pp. 882–888, 2003.

[6] J. Vlachogiannis and K. Lee, "A comparative study on particle swarm optimization for optimal steady-state performance of power systems," *Power Systems, IEEE Transactions on*, vol. 21, no. 4, pp. 1718–1728, 2006.

[7] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control, Second Edition*, 1996.