4

UNIT COMMITMENT

4.1 INTRODUCTION

Because human activity follows cycles, most systems supplying services to a large population will experience cycles. This includes transportation systems, communication systems, as well as electric power systems. In the case of an electric power system, the total load on the system will generally be higher during the daytime and early evening when industrial loads are high, lights are on, and so forth and lower during the late evening and early morning when most of the population is asleep. In addition, the use of electric power has a weekly cycle, the load being lower over weekend days than weekdays. But why is this a problem in the operation of an electric power system? Why not just simply commit enough units to cover the maximum system load and leave them running? Note that to "commit" a generating unit is to "turn it on," that is, to bring the unit up to speed, synchronize it to the system, and connect it so it can deliver power to the network. The problem with "commit enough units and leave them on-line" is one of economics. As will be shown in Example 4A, it is quite expensive to run too many generating units. A great deal of money can be saved by turning units off (decommitting them) when they are not needed.

4.1.1 Economic Dispatch versus Unit Commitment

At this point, it may be as well to emphasize the essential difference between the unit commitment and economic dispatch problem. The economic dispatch problem

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assumes that there are N_{gen} units already connected to the system. The purpose of the economic dispatch problem is to find the optimum operating policy for these N_{gen} units. This is the problem that we have been investigating so far in this text.

The unit commitment problem, on the other hand, is more complex. We may assume that we have N_{gen} units available to us and that we have a forecast of the demand to be served. The question that is asked in the unit commitment problem area is approximately as follows.

> Given that there are a number of subsets of the complete set of N_{gen} generating units that would satisfy the expected demand, which of these subsets should be used in order to provide the minimum operating cost?

This unit commitment problem may be extended over some period of time, such as the 24 h of a day or the 168 h of a week. The unit commitment problem is a much more difficult problem to solve. The solution procedures involve the economic dispatch problem as a subproblem. That is, for each of the subsets of the total number of units that are to be tested, for any given set of them connected to the load, the particular subset should be operated in optimum economic fashion. This will permit finding the minimum operating cost for that subset, but it does not establish which of the subsets is in fact the one that will give minimum cost over a period of time.

A later chapter will consider the unit commitment problem in some detail. The problem is more difficult to solve mathematically since it involves integer variables. That is, generating units must be either all on or all off. (How can you turn a switch half on?)

Example 4A: Suppose one had the three units given here:

$$\begin{aligned}
\textbf{Unit 1:}\quad & \text{Min} = 150\,\text{MW} \\
& \text{Max} = 600\,\text{MW} \\
& H_1 = 510.0 + 7.2P_1 + 0.00142P_1^2\ \text{MBtu/h}
\end{aligned}$$

$$\begin{aligned}
\textbf{Unit 2:}\quad & \text{Min} = 100\,\text{MW} \\
& \text{Max} = 400\,\text{MW} \\
& H_2 = 310.0 + 7.85P_2 + 0.00194P_2^2\ \text{MBtu/h}
\end{aligned}$$

$$\begin{aligned}
\textbf{Unit 3:}\quad & \text{Min} = 50\,\text{MW} \\
& \text{Max} = 200\,\text{MW} \\
& H_3 = 78.0 + 7.97P_3 + 0.00482P_3^2\ \text{MBtu/h}
\end{aligned}$$

with fuel costs:

$$\begin{aligned}
\text{Fuel cost}_1 &= 1.1\,\text{R/MBtu} \\
\text{Fuel cost}_2 &= 1.0\,\text{R/MBtu} \\
\text{Fuel cost}_3 &= 1.2\,\text{R/MBtu}
\end{aligned}$$

If we are to supply a load of 550 MW, what unit or combination of units should be used to supply this load most economically? To solve this problem, simply try all combinations of the three units. Some combinations will be infeasible if the sum of all maximum MW for the units committed is less than the load or if the sum of all minimum MW for the units committed is greater than the load. For each feasible combination, the units will be dispatched using the techniques of Chapter 3. The results are presented in Table 4.1.

Note that the least expensive way to supply the generation is not with all three units running or even any combination involving two units. Rather, the optimum commitment is to only run unit 1, the most economic unit. By only running the most economic unit, the load can be supplied by that unit operating closer to its best efficiency. If another unit is committed, both unit 1 and the other unit will be loaded further from their best efficiency points such that the net cost is greater than unit 1 alone.

Suppose the load follows a simple "peak-valley" pattern as shown in Figure 4.1. If the operation of the system is to be optimized, units must be shut down as the load goes down and then recommitted as it goes back up. We would like to know which units to drop and when. As we will show later, this problem is far from trivial when real generating units are considered. One approach to this solution is demonstrated in Example 4B, where a simple priority-list scheme is developed.

Example 4B: Suppose we wish to know which units to drop as a function of system load. Let the units and fuel costs be the same as in Example 4A, with the load varying from a peak of 1200 MW to a valley of 500 MW. To obtain a "shutdown rule," simply use a brute-force technique wherein all combinations of units will be tried (as in Example 4A) for each load value taken in steps of 50 MW from 1200 to 500. The results of applying this brute-force technique are given in Table 4.2. Our shutdown rule is quite simple.

> When load is above 1000 MW, run all three units; between 1000 and 600 MW, run units 1 and 2; below 600 MW, run only unit 1.

Figure 4.2 shows the unit commitment schedule derived from this shutdown rule as applied to the load curve of Figure 4.1.

So far, we have only obeyed one simple constraint: *Enough units will be committed to supply the load*. If this were all that was involved in the unit commitment problem—that is, just meeting the load—we could stop here and state that the problem was "solved." Unfortunately, other constraints and other phenomena must be taken into account in order to claim an optimum solution. These constraints will be discussed in the next section, followed by a description of some of the presently used methods of solution.

TABLE 4.1 Unit Combinations and Dispatch for 550-MW Load of Example 4A

Unit 1	Unit 2	Unit 3	Max Gen	Min Gen	P_1	P_2	P_3	F_1	F_2	F_3	Total Gen Cost $F_1 + F_2 + F_3$
Off	Off	Off	0	0							Infeasible
Off	Off	On	200	50							Infeasible
Off	On	Off	400	100							Infeasible
Off	On	On	600	150	0	400	150	0	3760	1658	5418
On	Off	Off	600	150	550	0	0	5389	0	0	5389
On	Off	On	800	200	500	0	50	4911	0	586	5497
On	On	Off	1000	250	295	255	0	3030	2440	0	5471
On	On	On	1200	300	267	233	50	2787	2244	586	5617

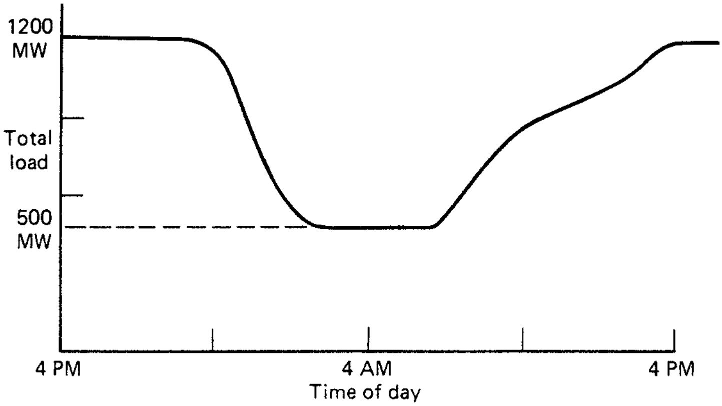

FIGURE 4.1 Simple "peak-valley" load pattern.

TABLE 4.2 "Shutdown Rule" Derivation for Example 4B

	Optimum Combination		
Load	Unit 1	Unit 2	Unit 3
1200	On	On	On
1150	On	On	On
1100	On	On	On
1050	On	On	On
1000	On	On	Off
950	On	On	Off
900	On	On	Off
850	On	On	Off
800	On	On	Off
750	On	On	Off
700	On	On	Off
650	On	On	Off
600	On	Off	Off
550	On	Off	Off
500	On	Off	Off

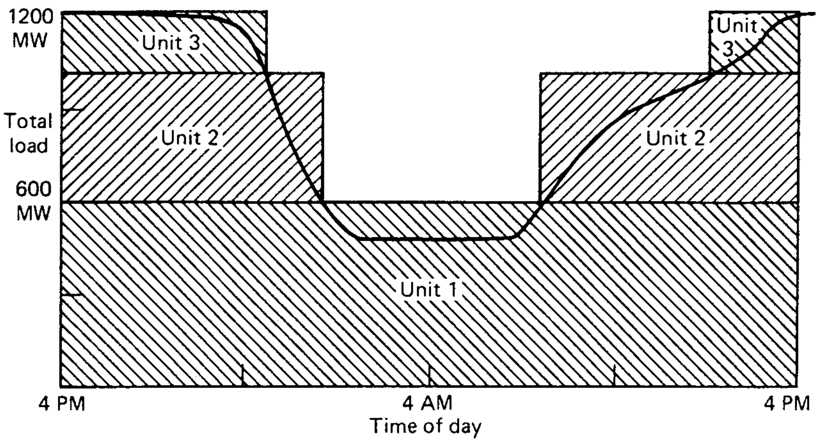

FIGURE 4.2 Unit commitment schedule using the shutdown rule.

4.1.2 Constraints in Unit Commitment

Many constraints can be placed on the unit commitment problem. The list presented here is by no means exhaustive. Each individual power system, power pool, reliability council, and so forth may impose different rules on the scheduling of units, depending on the generation makeup, load-curve characteristics, and such.

4.1.3 Spinning Reserve

Spinning reserve is the term used to describe the total amount of generation available from all units synchronized (i.e., spinning) on the system, minus the present load and losses being supplied. Spinning reserve must be carried so that the loss of one or more units does not cause too far a drop in system frequency (see Chapter 10). Quite simply, if one unit is lost, there must be ample reserve on the other units to make up for the loss in a specified time period.

Spinning reserve must be allocated to obey certain rules, usually set by regional reliability councils (in the United States) that (specify how the) reserve is to be allocated to various units. Typical rules specify that reserve must be a given percentage of forecasted peak demand or that reserve must be capable of making up the loss of the most heavily loaded unit in a given period of time. Others calculate reserve requirements as a function of the probability of not having sufficient generation to meet the load.

Not only must the reserve be sufficient to make up for a generating unit failure, but the reserves must be allocated among fast-responding units and slow-responding units. This allows the automatic generation control system (see Chapter 10) to restore frequency and interchange quickly in the event of a generating unit outage.

Beyond spinning reserve, the unit commitment problem may involve various classes of "scheduled reserves" or "off-line" reserves. These include quick-start diesel or gas-turbine units as well as most hydro-units and pumped-storage hydro-units that can be brought on-line, synchronized, and brought up to full capacity quickly. As such, these units can be "counted" in the overall reserve assessment, as long as their time to come up to full capacity is taken into account.

Reserves, finally, must be spread around the power system to avoid transmission system limitations (often called "bottling" of reserves) and to allow various parts of the system to run as "islands," should they become electrically disconnected.

Example 4C: Suppose a power system consisted of two isolated regions: a western region and an eastern region. Five units, as shown in Figure 4.3, have been committed to supply 3090 MW. The two regions are separated by transmission tie lines that can together transfer a maximum of 550 MW in either direction. This is also shown in Figure 4.3. What can we say about the allocation of spinning reserve in this system?

The data for the system in Figure 4.3 are given in Table 4.3. With the exception of unit 4, the loss of any unit on this system can be covered by the spinning reserve on the remaining units. Unit 4 presents a problem, however. If unit 4 were to be lost and unit 5 were to be run to its maximum of 600 MW, the eastern region would still need 590 MW to cover the load in that region. The 590 MW would have to be transmitted over the tie lines from the western region, which can easily supply 590 MW from its

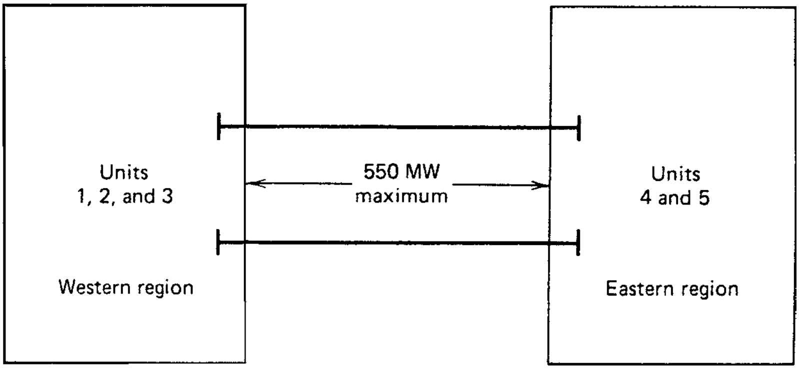

FIGURE 4.3 Two-region system.

TABLE 4.3 Data for the System in Figure 4.3

Region	Unit	Unit Capacity (MW)	Unit Output (MW)	Regional Generation (MW)	Spinning Reserve	Regional Load (MW)	Interchange (MW)
Western	1	1000	900		100		
	2	800	420	1740	380	1900	160 in
	3	800	420		380		
Eastern	4	1200	1040	1350	160	1190	160 out
	5	600	310		290		
Total	1–5	4400	3090	3090	1310	3090	

reserves. However, the tie capacity of only 550 MW limits the transfer. Therefore, the loss of unit 4 cannot be covered even though the entire system has ample reserves. The only solution to this problem is to commit more units to operate in the eastern region.

4.1.4 Thermal Unit Constraints

Thermal units usually require a crew to operate them, especially when turned on and turned off. A thermal unit can undergo only gradual temperature changes, and this translates into a time period of some hours required to bring the unit on-line. As a result of such restrictions in the operation of a thermal plant, various constraints arise, such as:

- **Minimum uptime**: once the unit is running, it should not be turned off immediately.
- **Minimum downtime**: once the unit is decommitted, there is a minimum time before it can be recommitted.
- **Crew constraints**: if a plant consists of two or more units, they cannot both be turned on at the same time since there are not enough crew members to attend both units while starting up.

In addition, because the temperature and pressure of the thermal unit must be moved slowly, a certain amount of energy must be expended to bring the unit on-line. This energy does not result in any MW generation from the unit and is brought into the unit commitment problem as a *start-up cost*.

The start-up cost can vary from a maximum "cold-start" value to a much smaller value if the unit was only turned off recently and is still relatively close to operating temperature. There are two approaches to treating a thermal unit during its down period. The first allows the unit's boiler to cool down and then heat back up to operating temperature in time for a scheduled turn on. The second (called *banking*) requires that sufficient energy be input to the boiler to just maintain operating temperature. The costs for the two can be compared so that, if possible, the best approach (cooling or banking) can be chosen.

$$\text{Start-up cost when cooling} = C_c\left(1-\varepsilon^{-t/\alpha}\right)\times F + C_f$$

where

$$\begin{aligned}
C_c &= \text{cold-start cost (MBtu)}\\
F &= \text{fuel cost}\\
C_f &= \text{fixed cost (includes crew expense, maintenance expenses) (in \$)}\\
\alpha &= \text{thermal time constant for the unit}\\
t &= \text{time (h) the unit was cooled}
\end{aligned}$$

$$\text{Start-up cost when banking} = C_t \times t \times F + C_f$$

where

$$C_t = \text{cost (MBtu / h) of maintaining unit at operating temperature}$$

Up to a certain number of hours, the cost of banking will be less than the cost of cooling, as is illustrated in Figure 4.4.

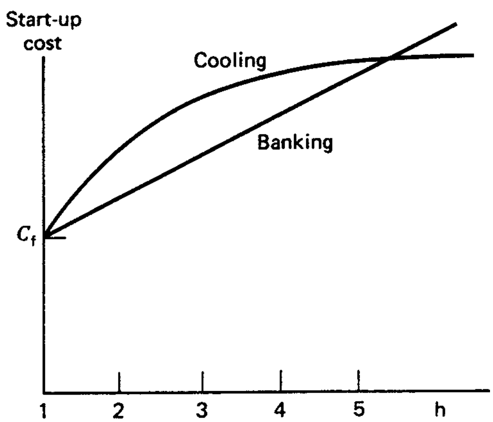

FIGURE 4.4 Time-dependent start-up costs.

Finally, the capacity limits of thermal units may change frequently, due to maintenance or unscheduled outages of various equipment in the plant; this must also be taken into account in unit commitment.

4.1.5 Other Constraints

4.1.5.1 Must Run. Some units are given a must-run status during certain times of the year for reason of voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself.

4.1.5.2 Fuel Constraints. We will treat the "fuel scheduling" problem briefly in Chapter 5. A system in which some units have limited fuel, or else have constraints that require them to burn a specified amount of fuel in a given time, presents a most challenging unit commitment problem.

4.1.5.3 Hydro-Constraints. Unit commitment cannot be completely separated from the scheduling of hydro-units. In this chapter, we will assume that the hydrothermal scheduling (or "coordination") problem can be separated from the unit commitment problem. We, of course, cannot assert flatly that our treatment in this fashion will always result in an optimal solution.

4.2 UNIT COMMITMENT SOLUTION METHODS

The commitment problem can be very difficult. As a theoretical exercise, let us postulate the following situation.

- We must establish a loading pattern for M periods.
- We have N_{gen} units to commit and dispatch.
- The M load levels and operating limits on the N_{gen} units are such that any one unit can supply the individual loads and that any combination of units can also supply the loads.

Next, assume we are going to establish the commitment by enumeration (brute force). The total number of combinations we need to try each hour is

$$C\left(N_{\text{gen}},1\right)+C\left(N_{\text{gen}},2\right)+\cdots+C\left(N_{\text{gen}},N_{\text{gen}}-1\right)+C\left(N_{\text{gen}},N_{\text{gen}}\right)=2^{N_{\text{gen}}}-1$$

where $C(N_{\text{gen}},j)$ is the combination of N_{gen} items taken j at a time. That is,

$$C(N_{\text{gen}},j)=\left[\frac{N_{\text{gen}}!}{(N_{\text{gen}}-j)!\,j!}\right]$$

$$j!=1\times 2\times 3\times\cdots\times j$$

For the total period of M intervals, the maximum number of possible combinations is $(2^{N_{gen}}-1)^M$, which can become a horrid number to think about.