Unit Commitment

- Economic Dispatch dealt with the problem of minimizing the cost of supplying the load with a given set of generators

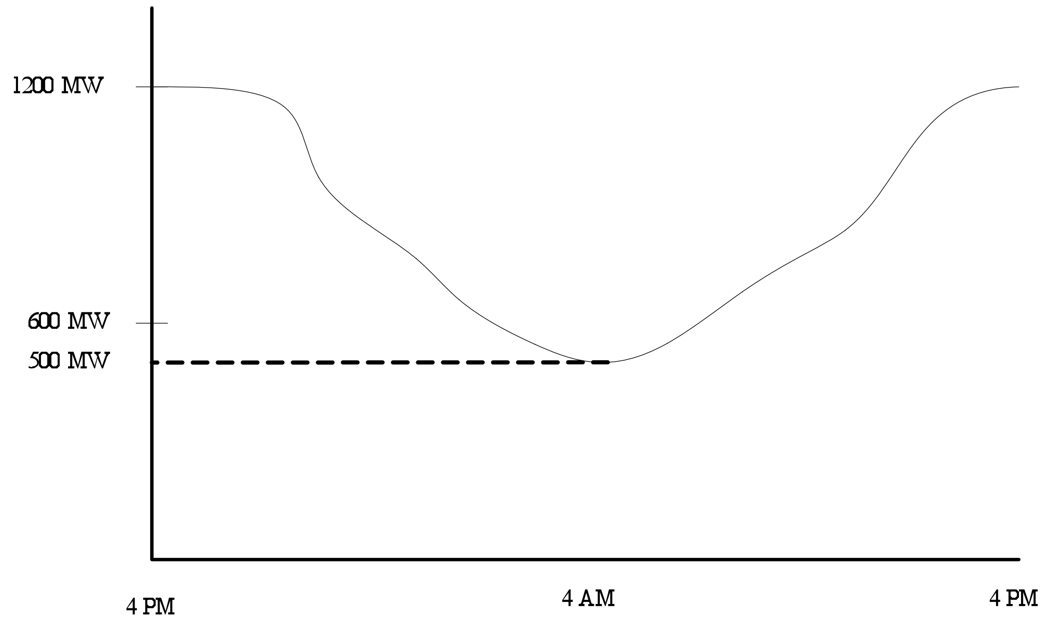
- Unit Commitment deals with the more complicated problem of minimizing the cost of supplying the load when the set of generators is also variable

- Calculating a unit commitment required the calculation of numerous Economic Dispatches

Unit Commitment

- Numerous economic dispatches are necessary because of the time varying nature of the electrical load

- Generators are generally re-dispatched every hour



Economic Dispatch for Unit Commitment

- Because of the large number economic dispatches that must be calculated it is common to use simplified versions of the previously discussed method

- The first method that we will examine is the "priority list" method

- The second method that we will examine is the "block counting" method

Generator Information (Wood and Wollenberg)

- **Unit 1:**
  - Max. Output= 600 MW
  - Min. Output= 150 MW
  - Fuel cost=1.1 \$/MBtu

$$H_1(P_1) = 510.0 + 7.2P_1 + .00142P_1^2$$

$$C_1(P_1) = 5.61 + 7.92P_1 + .001562P_1^2$$

- **Unit 2:**
  - Max. Output= 400 MW
  - Min. Output= 100 MW
  - Fuel cost=1.0 \$/MBtu

$$H_2(P_2) = 310.0 + 7.85P_2 + .00194P_2^2$$

$$C_2(P_2) = 310.0 + 7.85P_2 + .00194P_2^2$$

- **Unit 3:**
  - Max. Output= 200 MW
  - Min. Output= 50 MW
  - Fuel cost=1.2 \$/MBtu

$$H_3(P_3) = 78.0 + 7.97P_3 + .00482P_3^2$$

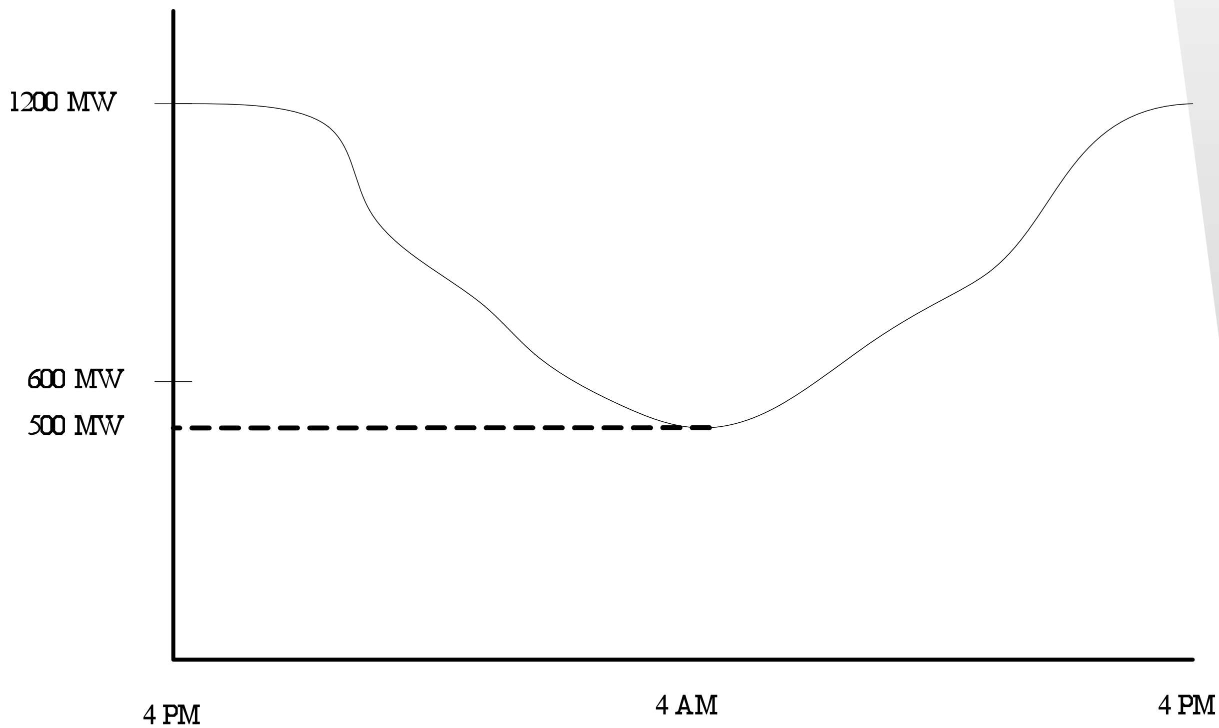
$$C_3(P_3) = 93.6 + 9.56P_3 + .00578P_3^2$$

Example Case 1 (Wood and Wollenberg)

550 MW Load

Unit 1	Unit 2	Unit 3	Max Gen	Min Gen	P1	P2	P3	C1	C2	C3	Total Cost
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	267	50	2787	2244	586	5617

Example Case 2 (Wood and Wollenberg) Cont

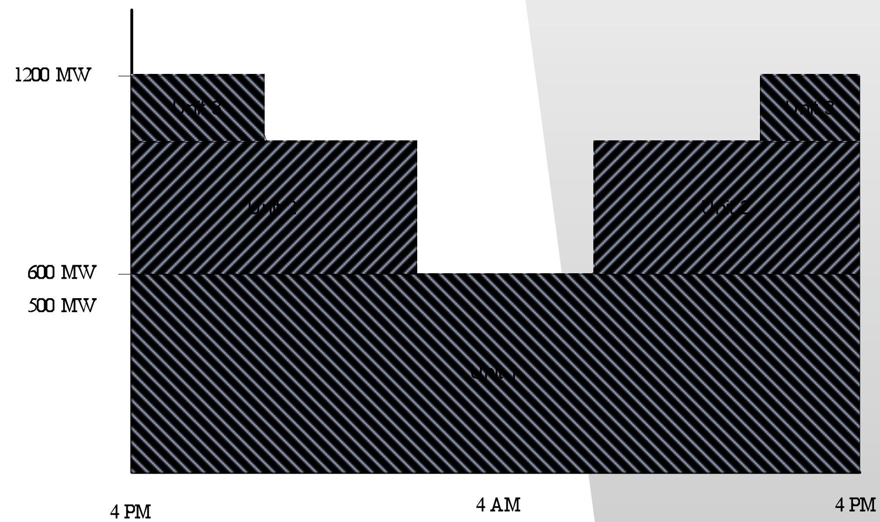


Example Case 2 (Wood and Wollenberg) Cont

- Priority list rules
  - Load<600MW, run only unit 1
  - 600MW<Load<1,000MW, run units 1 and 2
  - 1,000MW<Load, run all three units

Example Case 2 (Wood and Wollenberg) Cont

	Optimal 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



Block Counting Example

- In the previous priority list example a single set of rules was used to determine the economic dispatch

- In the block counting method each generator has its output separated into costs over ranges

  - Gen 1: \$10/MW 0-50MW
    \$12/MW 51-100MW

  - Gen 2: \$10/MW 0-25MW
    \$12/MW 26-100MW

Block Counting Example Cont.

- The total cost of operation is determined by adding generation until the load is met
- The lowest cost generation is added first and thereafter in ascending order
- When the generation meets the load the total cost is calculated

Block Counting Example Cont.

- Total Load=1000MW
  - Gen 1: \$8/MW 0-150MW
    \$10/MW 151-300MW
    \$12/MW 301-500MW
  - Gen 2: \$10/MW 0-125MW
    \$12/MW 126-250MW
    \$14/MW 251-500MW
  - Gen 3: \$9/MW 0-175MW
    \$10/MW 176-400MW
    \$12/MW 401-500MW

Block Counting Example Cont.

- Using the table to the right the generation is added in blocks from the three generators until the generation meets the load

- The table to the lower right shows the cost per MW for the various operating regions

	Gen 1	Gen 2	Gen 3
$ 8.00	150	0	0
$ 9.00	0	0	175
$ 10.00	150	125	225
$ 11.00	200	0	0
$ 12.00	0	125	100
$ 13.00	0	250	0

Load	$/MW
0-150	$ 8.00
151-325	$ 9.00
326-825	$ 10.00
826-1025	$ 11.00
1026-1250	$ 12.00
1251-1500	$ 13.00

Block Counting Example Cont.

- Total operating cost=$9,700.00 when Load=10,000MW
  - Generator 1
    - Output: 475MW
    - Cost: $4,625.00
  - Generator 2
    - Output: 125MW
    - Cost: $1,250.00
  - Generator 3
    - Output: 400MW
    - Cost: $3,825.00

Unit Commitment Complexity

- At each time period the number of states equals 2^N
- N is the number of units in the system
- Even for a simple system with only 10 generators there are 1024 possible system states
- For a number of these states an economic dispatch is not necessary since the generation will not be able to meet the load

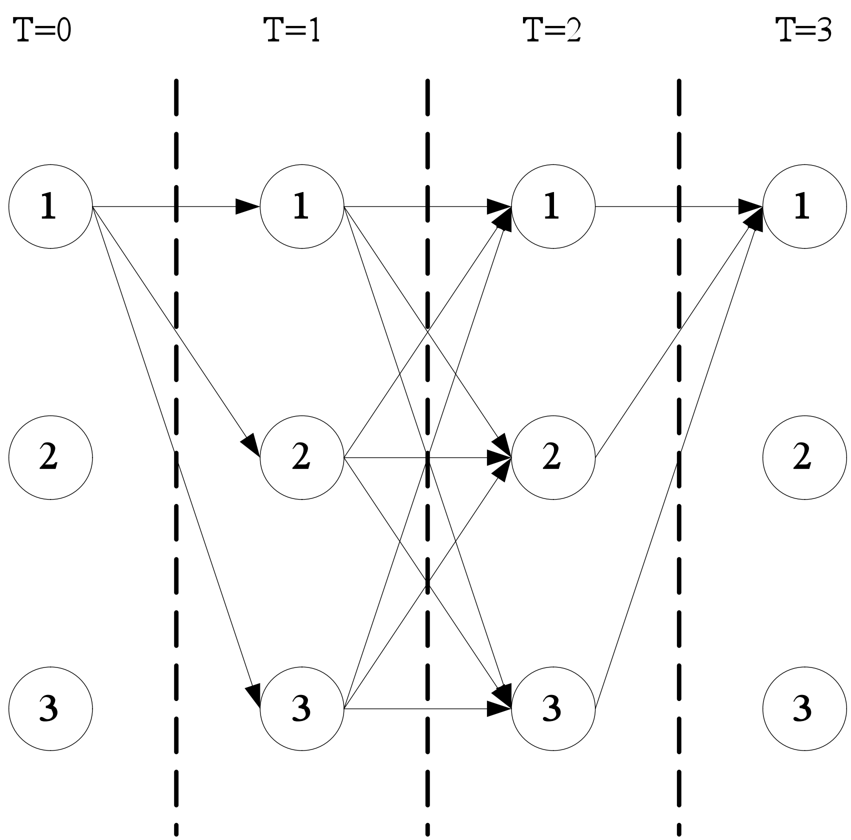
Unit Commitment Complexity Cont.

- Once the number of possible states at each time period is determined it is necessary to examine all of the possible state transitions

- When examining the complete enumeration of the problem there is the potential to transition from any initial state to any final state

- Once again examining the 10 generator system, over a 24 hour period, yields $1.76*10^{72}$ possible state transitions

Economic Dispatch Complexity Cont.



Unit Commitment Constraints

- Up to this point we have examined each of the states without regard for the transition to or from the state

- In an actual system there are numerous constraints

  - Spinning Reserve
  - Minimum up time
  - Minimum down time
  - Startup/Shutdown costs

Spinning Reserve

- Spinning reserve is defined as “the total amount of generation available from all synchronized units connected to the system, less the system load plus losses”

- Spinning reserved is used to ensure that there is sufficient generation to meet the demand under a given set of contingency conditions

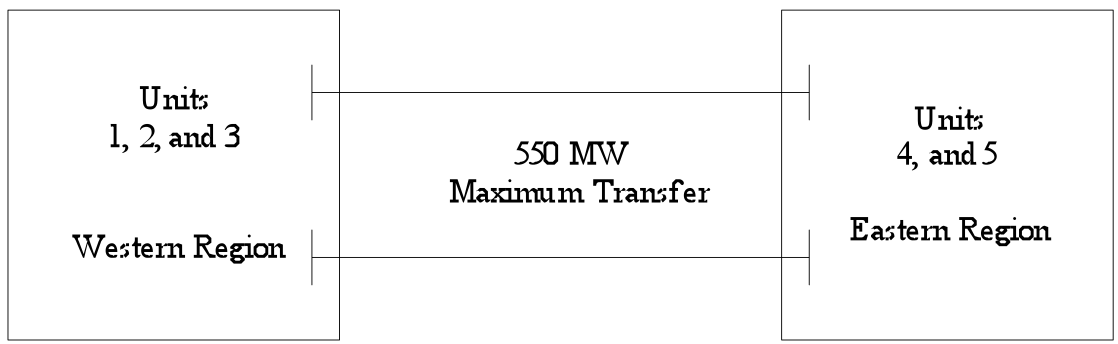
- A typical contingency condition is that the spinning reserve must be sufficient to allow for the loss of the largest generator in the system

Spinning Reserve Cont.

- Spinning reserves must also meet time requirements and can be classified according to time
  - In general only generators with high ramp rates are used
  - Some combustion turbines are used that are normally not running, but they can be brought up to speed and synchronized quickly

- Spinning reserves must be allocated across a system to prevent transmission congestion
  - This is especially true in areas where there are significant imports

Example Case 5 (Wood and Wollenberg)



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

Min Up/Down Times

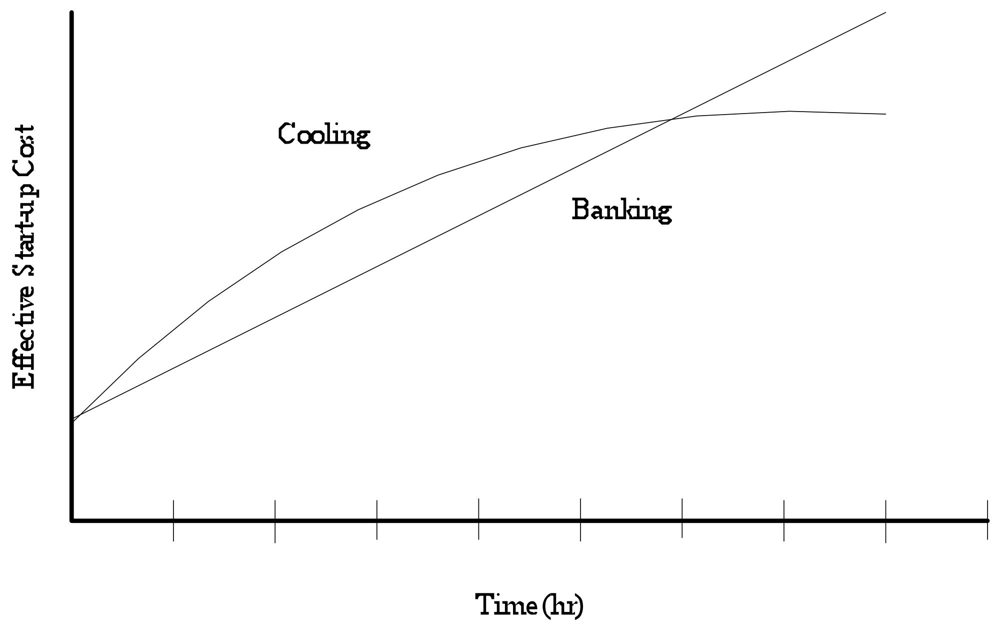
- Minimum up-time
  - Once the unit is started it should remain running for a minimum amount of time
  - In a thermal plant or combustion turbine it may be necessary to allow a generator to fully heat up for a period of time, failure to do so can result in reduction of unit life

- Minimum down-time
  - Once the unit is shutdown it must remain down for a minimum amount of time
  - Xeon build-up in nuclear plants is an excellent example of a minimum downtime
  - If a nuclear plant is at high power for a prolonged period and then shut down, it may be physically impossible to restart the reactor until the Xeon decays

Banking or Cooling to Cold Iron

- When a generator is shut down it can either be allowed to cool down or it can be "banked" and kept at operating temperature
- Full cool down to "cold iron" is only allowed when the plant is expected to be shutdown for a long period of time
- A generator is "banked" when it is expected to re-dispatched in a short period of time
- For each plant there is a break even point between cooling down and banking

Banking or Cooling to Cold Iron Cont.

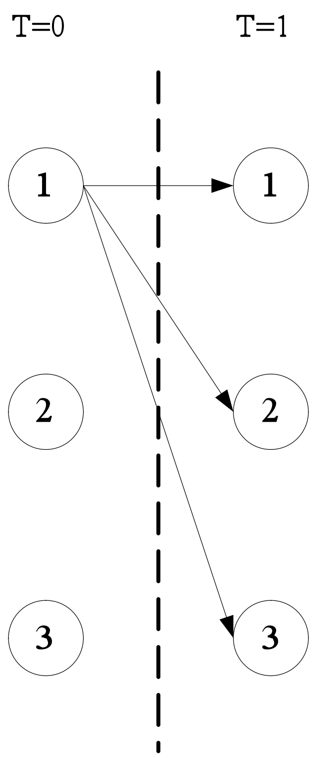


➢At some point the cost of continual banking exceeds the cost of heating the plant from cold iron to normal operating temperature

Startup/Shutdown Costs

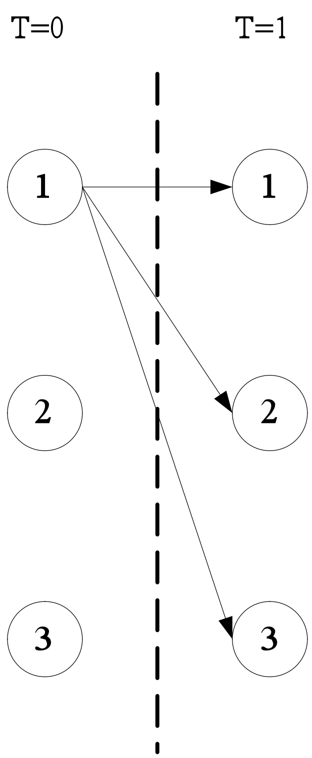
- In general there are costs associated with starting up or shutting down a generator
- For a thermal plant heat is required to bring a generator from "cold iron" to the operating temperature, during which time no electrical power is produced
- Due to personnel requirements it may not be possible to startup or shutdown 2 generators at the same time
- These cost must be considered when transitioning from one state to the next

Startup/Shutdown Costs Cont.



- State 1
  - Gen 1:0
  - Gen 2:1
  - Gen 3:1
- State 2
  - Gen 1:1
  - Gen 2:1
  - Gen 3:1
- State 3
  - Gen 1:1
  - Gen 2:1
  - Gen 3:0

Startup/Shutdown Costs Cont.



$$\$ = ED_1^{t=0} + \left(state_1^{t=0} \rightarrow state_1^{t=1}\right) + ED_1^{t=1} = ED_1^{t=0} + ED_1^{t=1}$$

$$\$ = ED_1^{t=0} + \left(state_1^{t=0} \rightarrow state_2^{t=1}\right) + ED_2^{t=1} = ED_1^{t=0} + SU_{gen1} + ED_2^{t=1}$$

$$\$ = ED_1^{t=0} + \left(state_1^{t=0} \rightarrow state_3^{t=1}\right) + ED_3^{t=1} = ED_1^{t=0} + \left(SU_{gen1} + SD_{gen3}\right) + ED_3^{t=1}$$

Dynamic Programming Solution Method

- The forward method of dynamic programming has distinct advantages
- With the forward method the problem progresses forward from an initial unit dispatch
- In this way all possible and/or viable states and state transitions can be examined
- Dynamic programming allows for the inclusion of system constraints

Dynamic Programming Solution Method Cont.

- Using the forward dynamic programming (FDP) with a strict priority list will be the examined method
- This method has the advantage of reducing the number of combinations that need to be investigated
- All states are ranked according to their total MW capacity
- All cost functions will be linear, resulting in a constant for the incremental cost (IC)

Example Case 1 (Wood and Wollenberg)

Unit	Max	Min	Heat Rate	No-Load Cost	IC	Min up	Min down
	MW	MW	Btu/kWh	$/hr	$/mWh	hr	hr
1	80	25	10440	213	23.54	4	2
2	250	60	9000	585.62	20.34	5	3
3	300	75	8730	684.74	19.74	5	4
4	60	20	11900	252	28	1	1

Unit	Initial Condition	Start-up Cost		
	hrs on/off	hot	cold	cold start
1	-5	150	350	4
2	8	170	400	5
3	8	500	1100	5
4	-6	0	0.02	0

Example Case 1 (Wood and Wollenberg) Cont.

State	Units				Max Capacity
15	1	1	1	1	690
14	1	1	1	0	630
13	0	1	1	1	610
12	0	1	1	0	550
11	1	0	1	1	440
10	1	1	0	1	390
9	1	0	1	0	380
8	0	0	1	1	360
7	1	1	0	0	330
6	0	1	0	1	310
5	0	0	1	0	300
4	0	1	0	0	250
3	1	0	0	1	140
2	1	0	0	0	80
1	0	0	0	1	60
0	0	0	0	0	0

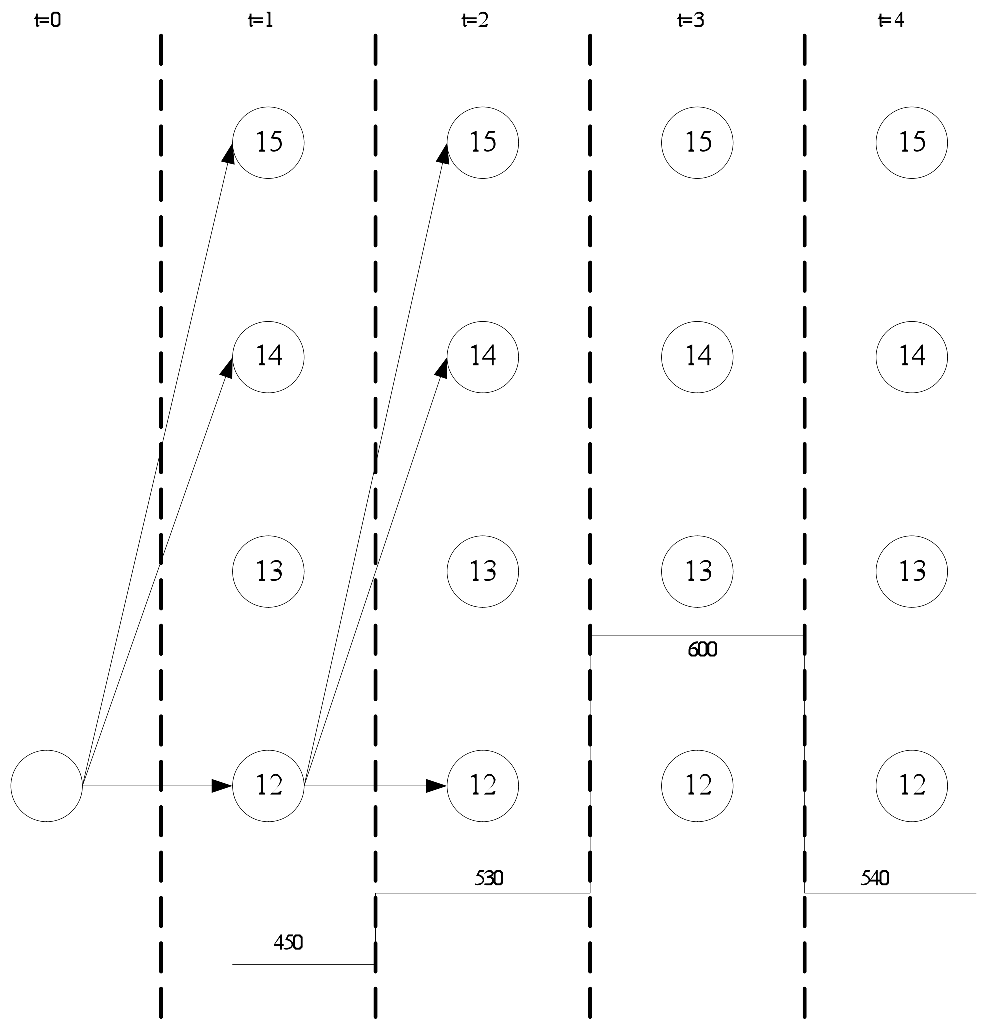
Load Pattern	
hr	Load (MW)
1	450
2	530
3	600
4	540
5	400
6	280
7	290
8	500

Example Case 1 (Wood and Wollenberg) Cont.

- In order to make the problem more manageable only 4 of the 16 states will be considered

State	Units				Max Capacity
5	0	0	1	0	300
12	0	1	1	0	550
14	1	1	1	0	630
15	1	1	1	1	690

Example Case 1 (Wood and Wollenberg) Cont.



Example Case 1 (Wood and Wollenberg) Cont.

- Recursive algorithm for the FDP

$$F_{COST}(K,I) = \min\left[P_{COST}(K,I) + S_{COST}(K-1,L:K,I) + F_{COST}(K-1,L)\right]$$

$F_{COST}(K,I)$: least total cost to arrive at state (K,I)

$P_{COST}(K,I)$: production cost for state (K,I)

$S_{COST}(K-1,L:K,I)$: transition cost from state (K-1,L) to (K,I)

Example Case 1 (Wood and Wollenberg) Cont.

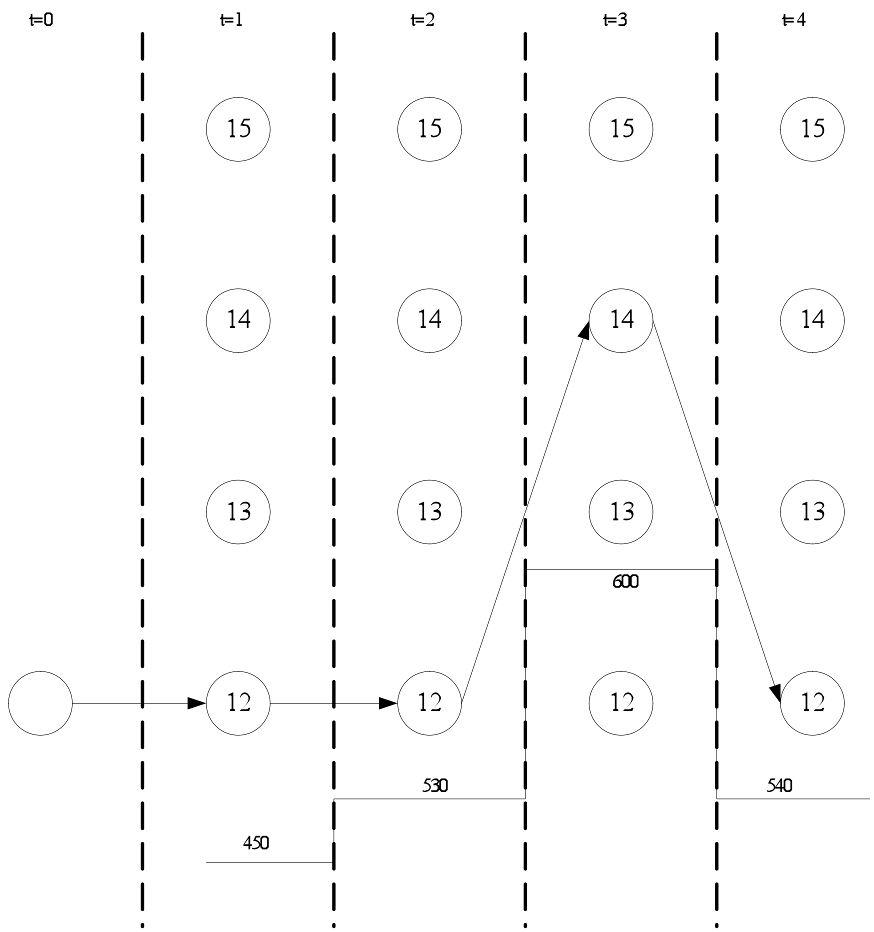
- From the initial state at t=0 there are 3 possible states to transition to, state 5 is excluded for capacity reasons

$$F_{COST}(1,15) = P_{COST}(1,15) + S_{COST}(0,12:1,15) = 9861 + 350 = 10,211$$

$$F_{COST}(1,14) = P_{COST}(1,14) + S_{COST}(0,12:1,14) = 9493 + 350 = 9,843$$

$$F_{COST}(1,12) = P_{COST}(1,12) + S_{COST}(0,12:1,12) = 9208 + 0 = 9,208$$

Example Case 1 (Wood and Wollenberg) Cont.



- For the first 4 time periods the optimal unit commitment is shown
- Minimum up and down times were not considered in this example
- A reduced set of states was used to reduce the computational requirements
- This simplification will lead to a greater than minimum operating cost

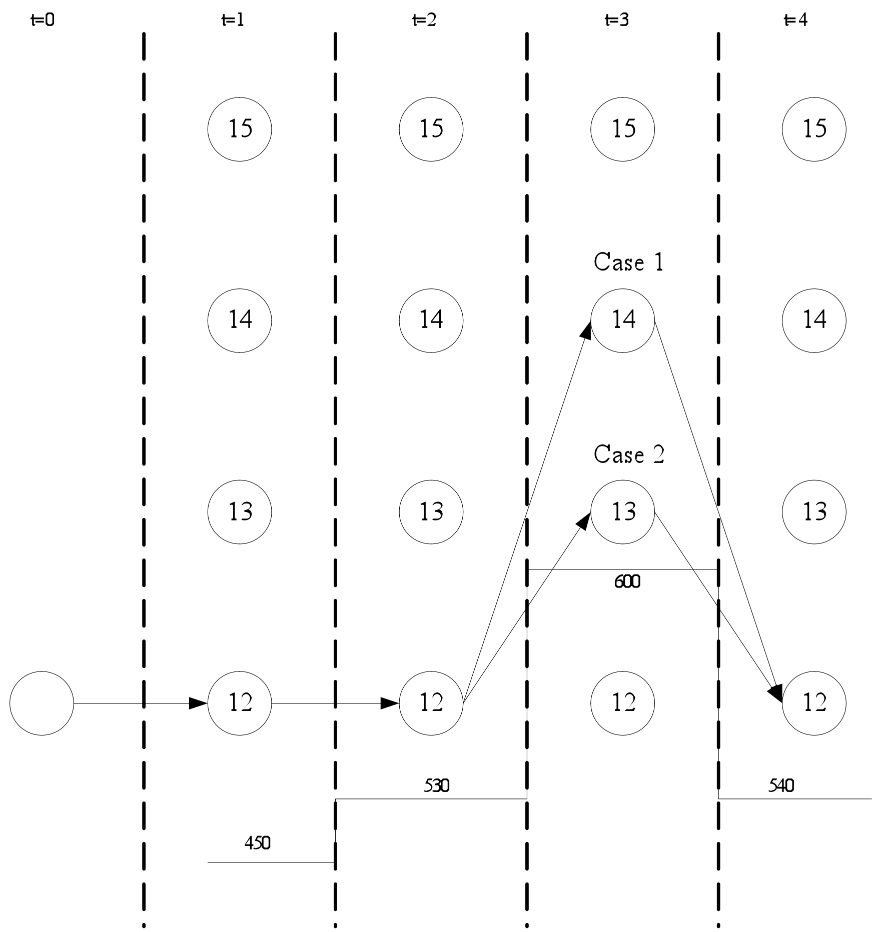
Example Case 2 (Wood and Wollenberg)

- In the previous case the number of state was limited to 5, 12, 14, and 15
- In this example all 15 of the states will be allowed, this is the complete enumeration method
- In a practical system the complete enumeration method is not practical

Example Case 2 (Wood and Wollenberg)

- The difference in the solution between case 1 and 2 occurs at t=3
- At t=3 case 1 dispatched generator 4 for 1 hour and then shut it down
- When all possible states are considered the option to start generation 1 is available
- While generator 4 is more expensive to operate than 1, it does not have an associated start up cost
- This type of unit is referred to as a “peaking” unit

Example Case 2 (Wood and Wollenberg)



Peaking Units

- Peaking units are generally non-thermal combustion turbines

- Peaking units are economically suited to short duration operations with relatively high ramp rates

- They are also used during high load periods when electricity is selling at higher rates

- Other rapid response generators such as hydro-plant can perform many of the functions of peaking plants

Ramp Rates

- Generators can only change their output power at a finite rate

- For large thermal plants this is especially true

- If there is a short spike in load followed by a reduction, it may be advantageous to begin reducing the output power of low ramp rate generators before the peak

- This prevents having excessive generation when the load begins to fall

Example Comparisons

- The total cost of operation for case 1=$74,439

- The total cost of operation for case 2=$73,274

- The second case yields the true optimal commitment, but at a cost of computational requirements

- In practical systems there is no guarantee that the unit commitment is the global optimum since the complete enumeration is not practical