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Thermal Generators Integrated with Wind Units for Profit Maximization in Deregulated Electricity Market

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ABSTRACT

This work presents the profit maximization of thermal generators along with wind units. 10 thermal generators are considered as a GENCO'S for 24 hour pattern. 25 Identical wind units as a wind farm is integrated with thermal units to maximize the profit, thereby reducing the cost of thermal units. Dynamic Programming (DP) is used to solve this multi-objective complex problem. The results in terms of profit are compared with thermal generators without wind and thermal generators with wind units.

INTRODUCTION

Unit commitment (UC) is a nonlinear mixed integer optimization problem to schedule the operation of the generating units at minimum operating cost while satisfying the demand and other equality and inequality constrains. The UC problem has to determine the on/off state of the generating units at each hour of the planning period and optimally dispatch the load among the committed units. UC is the most significant optimization task in the operation of the power systems. Solving the UC problem for large power systems is computationally expensive. The complexity of the UC problems grows exponentially to the number of generating units. Several solution strategies have been proposed to provide quality solutions to the UC problem and increase the potential savings of the power system operation. These include deterministic and stochastic search approaches. Deterministic approaches include the priority list method, dynamic programming, Lagrangian Relaxation and the branch and- bound methods. Although these methods are simple and fast, they suffer from numerical convergence and solution quality problems. The stochastic search algorithms such as particle swarm optimization, genetic algorithms, evolutionary programming, simulated annealing, ant colony optimization and tabu search are able to overcome the shortcomings of traditional optimization techniques. These methods can handle complex nonlinear constraints and provide high quality solutions. This formulation drastically reduces the number of decision variables and hence can overcome the shortcomings of stochastic search algorithms for UC problems.

OBJECTIVE FUNCTION

Objective Function

The objective function of thermal unit commitment problem is to minimize the total cost while satisfying several constraints.

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

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

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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 state (K, I) (K, I) is the Ith combination in hour

CONSTRAINTS IN UNIT COMMITMENT

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, which in turn translates into a time period of some hours that are required to bring the unit "online". As a result of such restrictions various constraints arise, in the operation of a thermal plant, such as:

Minimum up time

Once the unit is running, it cannot be turned off immediately.

$$T_i^{on} \le X_i^{on}(t)$$

T_i^{on} = minimum up time of unit '*i*'

Minimum down time

Once the unit is recommitted, there is a minimum time before it can be recommitted.

$$T_i^{off} \le X_i^{off}(t)$$

$$T_i^{off} = minimum\, down\, time\, of\ unit\ 'i'$$

System power balance

The total power output from the thermal generators and wind-battery should exactly satisfy the load demand for that hour and corresponding network loss. Thus the system power balance equation for hour t can be expressed

$$\sum_{i=1}^{N} P_i(t) + P_w(t) = P_D(t)$$

Power output from wind energy system

In practice the wind spills through the gap between the blades resulting in spillage loss. Therefore, the real power (P) delivered by a wind-turbine is less than the total power in the wind stream.

SOLUTION METHODOLOGY

Dynamic optimization is a mathematical optimization technique. Decomposes a problem into a series of problems, solves them, and develops an optimal solution to the original problem step by step. The method takes much less time than naïve methods. Optimal solutions of sub problems can be used to find the optimal solutions of the overall problem.

ALGORITHM OUTLINE

FORWARD DP ALGORITHM

Step 1: Calculate the production cost, P_{cost} for all feasible states I, for each hour.

Step 2: Calculate the total cost for R = 1, the transition cost is zero for the first hour. Save the minimum total cost value.

Step 3: Calculate the total minimum cost for the next hour. Now the transition cost is the minimum cost of the previous hour.

Step 4: Repeat Step 3 until the last hour to obtain the optimal schedule.

THERMAL UNITS - INPUTS, LOAD PATTERN

1 LOAD PATTERN FOR 10 THERMAL UNITS

Ten units are to be committed to serve 24-h load pattern. Data on the load pattern are contained in the given Table 4.1. The details of fuel cost components, initial conditions and load pattern are in table: 4.1

Table 4.1

Hour(h)	*Load(MW)*	*Price(Rs/MWh)*
1	700	996.75
2	750	990
3	850	1039.5
4	950	1019.25
5	1000	1046.25
6	1100	1032.75
7	1150	1012.5
8	1200	996.75
9	1300	1026
10	1400	1320.75
11	1450	1356.75
12	1500	1424.25
13	1400	1107
14	1300	1102.5
15	1200	1012.5
16	1050	1003.5
17	1000	1001.25
18	1100	990.25
19	1200	999
20	1400	1019.25
21	1300	1039.5
22	1100	1032.75
23	900	1023.75
24	800	1014.75

2. LOAD CURVE

The following graph has been obtained after computing the percentage change in profit after addition of a wind unit with the 10 unit’s thermal system. The respective load demand & change in profit percent has been shown for the corresponding hours.

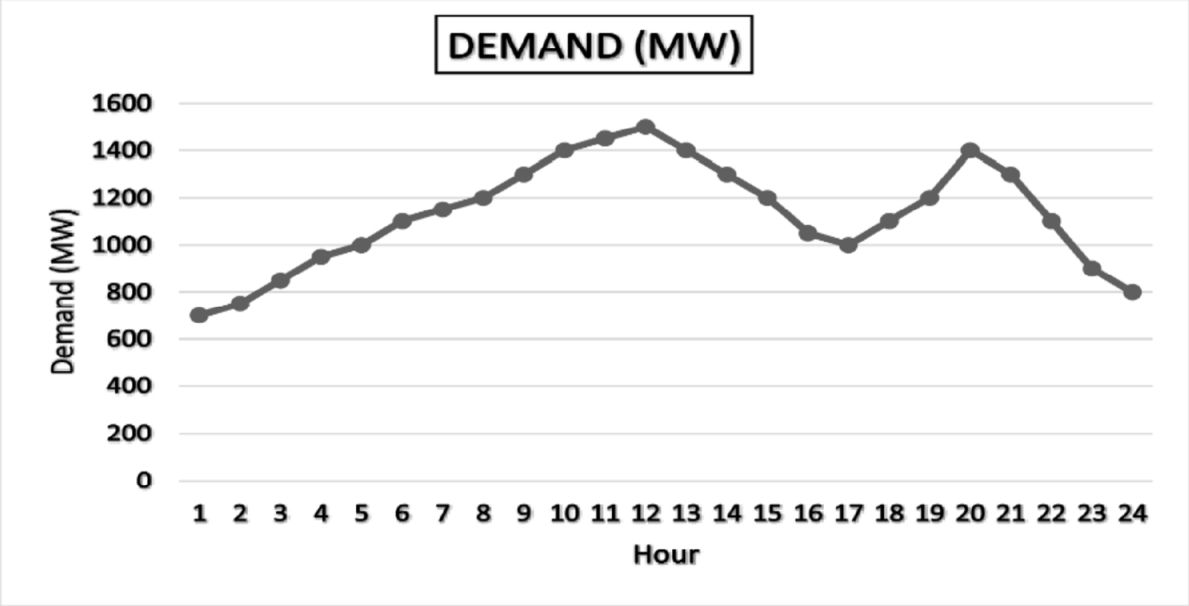


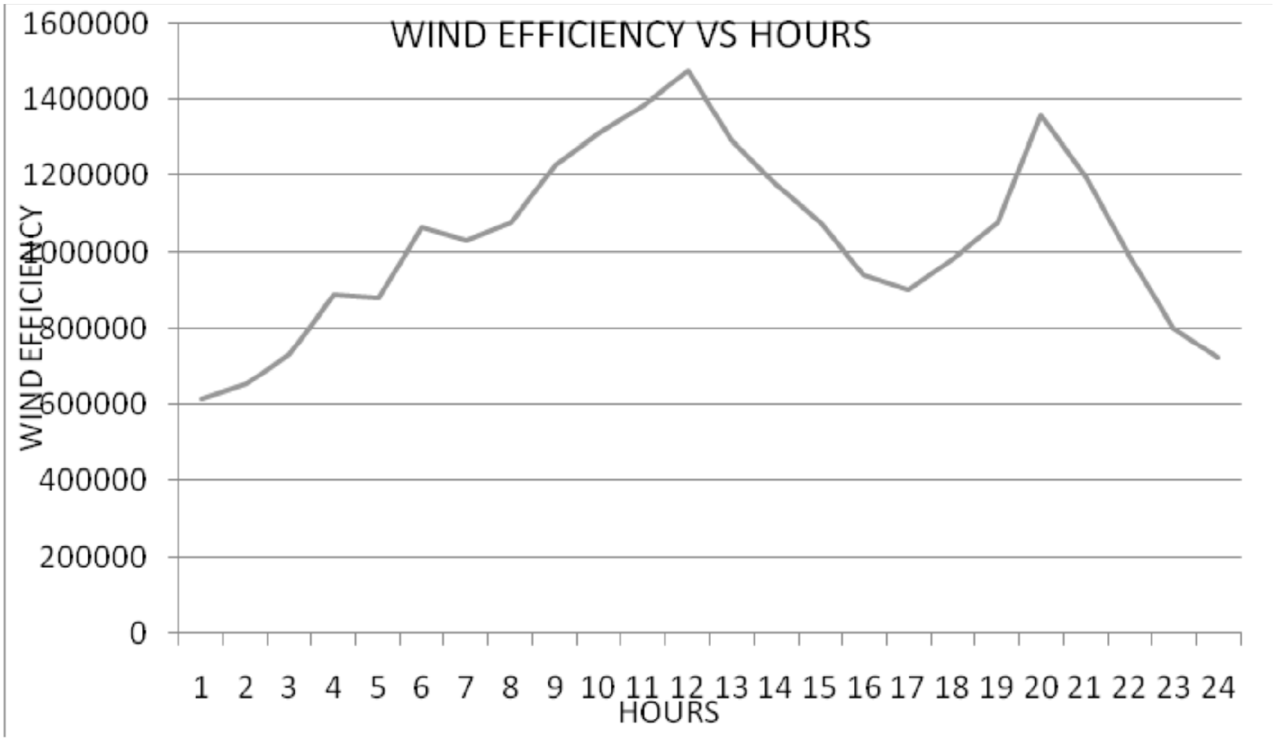
Fig. 4.1 Load Curve

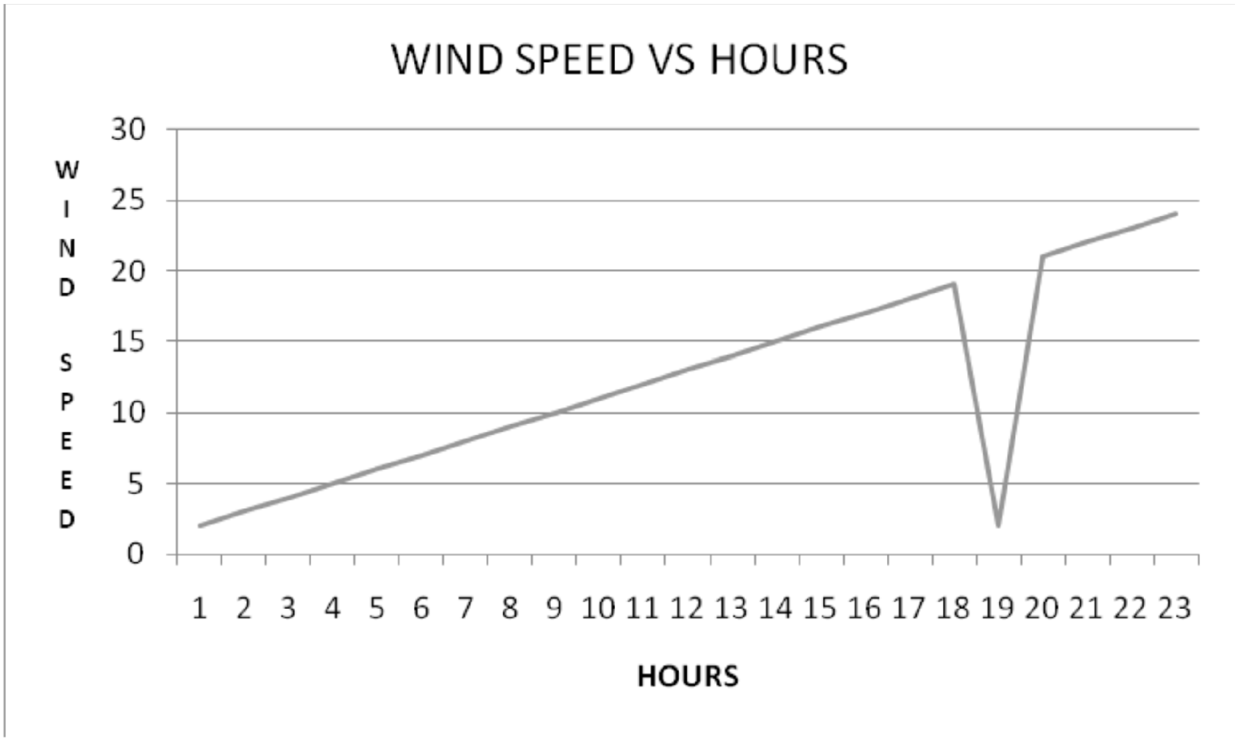
INPUT DATA FOR 10 UNITS

	Unit1	**Unit2**	**Unit3**	**Unit4**	**Unit5**	**Unit6**	**Unit7**	**Unit8**	**Unit9**	**Unit10**
P_i(max) (MW)	455	455	130	130	162	80	85	55	55	55
P_i(min) (MW)	150	150	20	20	25	20	25	10	10	10
A_i	1000	970	700	680	450	370	480	660	665	670
B_i	16.16	17.26	16.60	16.50	19.70	22.26	27.74	25.92	27.27	25.92
C_i	.00048	.00031	.002	.00211	.00398	.00712	.00079	.00413	.00222	.00173
MUT_i	8	8	5	5	6	3	3	1	1	1
MDT_i	8	8	5	5	6	3	3	1	1	1
$H_{cost}(i)$	4500	5000	550	560	900	170	260	30	30	30
$C_{cost}(i)$	9000	10000	11000	1120	1800	340	520	60	60	60
$C_{hour}(i)$	5	5	4	4	4	2	2	0	0	0
I state	8	8	-5	-5	-6	-3	-3	-1	-1	-1

WIND TURBINE

Hours	*Wind speed (m/s)*	*Overall efficiency*
1	2	0
2	3	0
3	4	0.223
4	5	0.388
5	6	0.436
6	7	0.457
7	8	0.462
8	9	0.450
9	10	0.425
10	11	0.388
11	12	0.340
12	13	0.284
13	14	0.223
14	15	0.190
15	16	0.157
16	17	0.131
17	18	0.110
18	19	0.094
19	20	0.080
20	21	0.069
21	22	0.060
22	23	0.053
23	24	0.046
24	25	0.041





OUTPUT OT 10 THERMAL UNIT SYSTEMS WITH ECONOMIC SCHEDULING WITHOUT WIND

Results are tabulated according to given data for the ten generator unit commitment problem. Here the total operating cost (Generation Cost), Selling Price per Unit & Profit Obtained is calculated.

Hours	*Demand (MW)*	*Rs/MWh*	*Total Cost in Rs*	*Price in Rs*	*Profit in Rs*
1	700	996.75	615740.8	697725	81985
2	750	990	654952.5	742500	87548
3	850	1039.5	733585	883575	149990
4	950	1019.25	889095.6	968287.5	129591.9
5	1000	1046.25	878074.7	1046250	168176
6	1100	1032.75	1064712.9	1136025	152312.1
7	1150	1012.5	1029560.6	1164375	134815
8	1200	996.75	1076303.1	1196100	119796.9
9	1300	1026	1227780.9	1333800	155519.1
10	1400	1320.75	1309869.6	1849050	554480.4
11	1450	1356.75	1384150.6	1967288	585836.9
12	1500	1424.25	1474802.9	2136375	664272.1
13	1400	1107	1294569.6	1549800	255230.4
14	1300	1102.5	1178280.9	1433250	254969.1
15	1200	1012.5	1076303.1	1215000	138696.9
16	1050	1003.5	940314.8	1053675	113360.2
17	1000	1001.25	900900.9	1001250	100349.1
18	1100	992.25	983712.9	1091475	107762.1
19	1200	999	1076303.1	1198800	122496.9
20	1400	1019.25	1359369.6	1426950	132380.4
21	1300	1039.5	1196503.4	1351350	154846.6
22	1100	1032.75	988934.9	1136025	147090.1
23	900	1023.75	800787.7	921375	120587.3
24	800	1014.75	722378	811800	89422
		Total	24856988.1	29312100	4721515

WIND POWER OUTPUT FROM THE WIND FARM

Results are tabulated according to the given data for 25 identical Wind Turbines in a Wind farm. Here the Power Developed at each hour is calculated according to varying Wind Speeds.

Hour	*Wind Speed (m/s)*	*Power Developed (MW)*
1	2	0
2	3	0
3	4	0.1251
4	5	0.4252
5	6	0.8257
6	7	1.3743
7	8	2.0738
8	9	2.8761
9	10	3.7261
10	11	4.5277
11	12	5.1509
12	13	5.4703
13	14	5.6054
14	15	5.622
15	16	5.638
16	17	5.6426
17	18	5.6244
18	19	5.6527
19	2	5.611
20	21	5.6024
21	22	5.6012
22	23	5.6536
23	24	5.5751
24	25	5.6165

WIND VELOCITY VS WIND POWER GRAPH

Wind Velocity Vs Wind Power graph is obtained according to the output obtained from the Wind farm for a single wind turbine. The power is changing almost linearly between cut-in speed and rated speed. But the Power becomes almost constant above rated speed and cut-off speed.

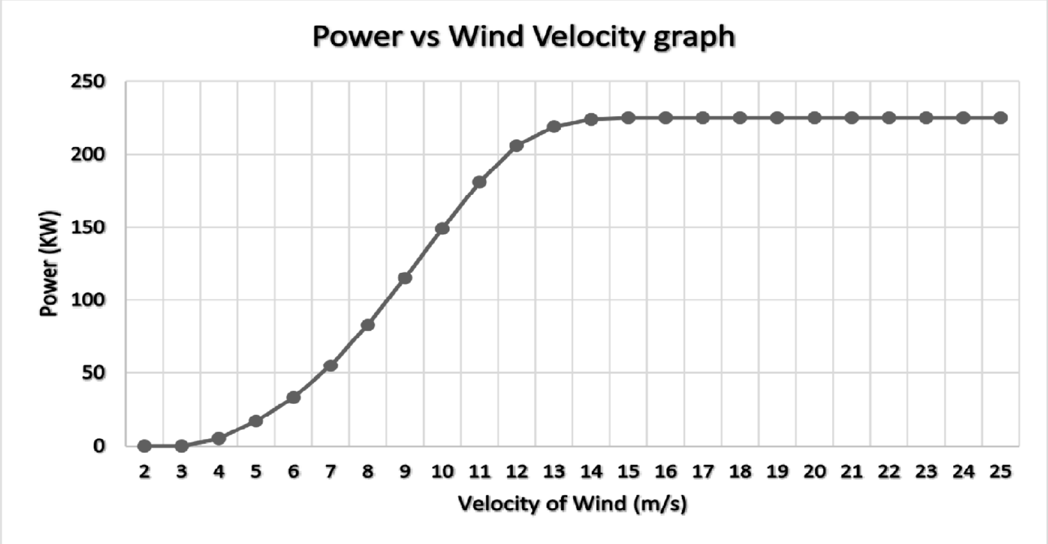
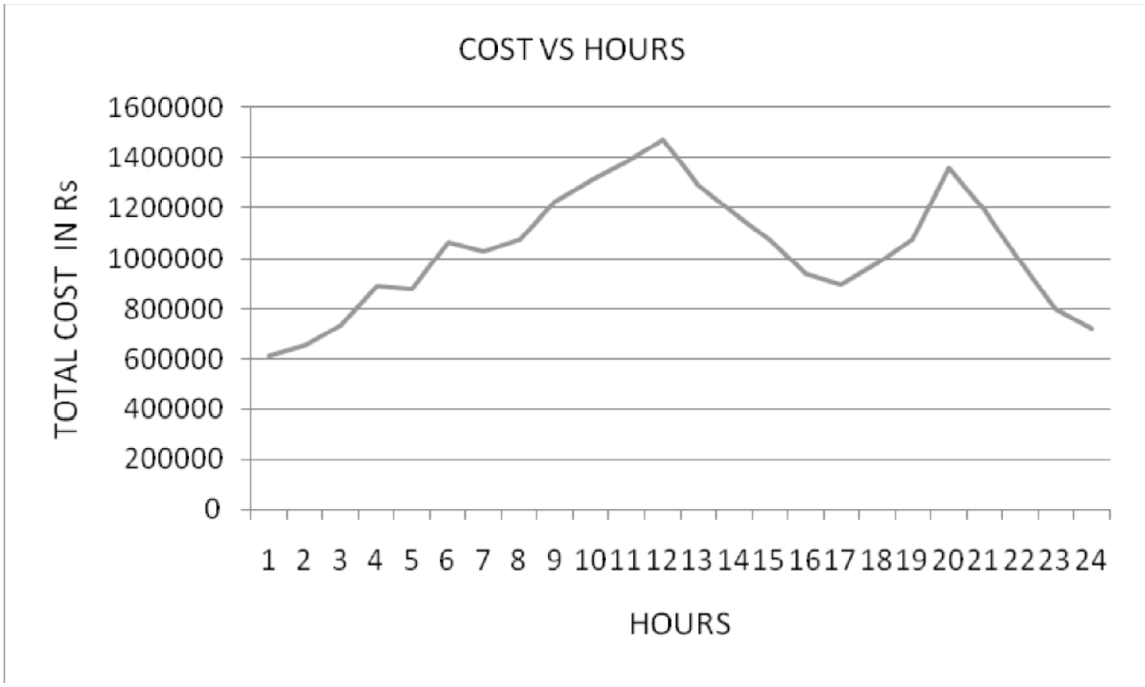


Figure 6.1: Power VS wind velocity graph



OUTPUT AND COMPARISION OF RESULTS OF WIND-THERMAL UNITS WITH ONLY THERMAL UNITS

Output of 10 unit systems with economic scheduling with wind

Results are tabulated according to given data for the ten generator unit commitment problem. Here the total operating cost is calculated, the unit combination selected in each hour and the distribution of load among each unit.

Hrs.	*U1*	*U2*	*U3*	*U4*	*U5*	*U6*	*U7*	*U8*	*U9*	*U10*	*Wind Unit*	*Genera-tion (MW)*	*Demand (MW)*	*Total Cost in Rs*
1	455	245	0	0	0	0	0	0	0	0	0	700	700	615740.8
2	455	295	0	0	0	0	0	0	0	0	0	750	750	654952.5
3	455	394.9	0	0	0	0	0	0	0	0	0.1251	850	850	733506.3
4	455	364.6	0	130	0	0	0	0	0	0	0.4252	950	950	888780.9
5	455	414.2	0	130	0	0	0	0	0	0	0.8257	1000	1000	877444.1
6	455	455	0	130	58.6	0	0	0	0	0	1.3743	1100	1100	1063442.1
7	455	455	0	130	107.9	0	0	0	0	0	2.0738	1150	1150	1027616.6
8	455	455	0	130	157.1	0	0	0	0	0	2.8761	1200	1200	1073567.6
9	455	455	130	130	126.3	0	0	0	0	0	3.7261	1300	1300	1224331
10	455	455	130	130	162	63.5	0	0	0	0	4.5277	1400	1400	1305172.3
11	455	455	130	130	162	80	32.8	0	0	0	5.1509	1450	1450	1393141.5
12	455	455	130	130	162	80	82.5	0	0	0	5.4703	1500	1500	1431985.7
13	455	455	130	130	162	0	62.4	0	0	0	5.6054	1400	1400	1307954.8
14	455	455	130	130	124.4	0	0	0	0	0	5.622	1300	1300	1173061.4
15	455	455	0	130	154.4	0	0	0	0	0	5.638	1200	1200	1071023.4
16	455	434.4	0	130	25	0	0	0	0	0	5.6426	1050	1050	935897
17	455	384.4	0	130	25	0	0	0	0	0	5.6244	1000	1000	896490.9

Hrs.	*U1*	*U2*	*U3*	*U4*	*U5*	*U6*	*U7*	*U8*	*U9*	*U10*	*Wind Unit*	*Genera-tion (MW)*	*Demand (MW)*	*Total Cost in Rs*
18	455	455	0	130	54.3	0	0	0	0	0	5.6527	1100	1100	978543.2
19	455	455	0	130	154.4	0	0	0	0	0	5.611	1200	1200	1071023.4
20	455	455	130	130	162	62.4	0	0	0	0	5.6024	1400	1400	1353526.1
21	455	455	130	130	104.4	20	0	0	0	0	5.6012	1300	1300	1191324
22	455	455	130	0	0	54.3	0	0	0	0	5.6536	1100	1100	983016.5
23	455	309.4	130	0	0	0	0	0	0	0	5.5751	900	900	796389.4
24	455	209.4	130	0	0	0	0	0	0	0	5.6165	800	800	717995.7
													TOTAL	24765927.2

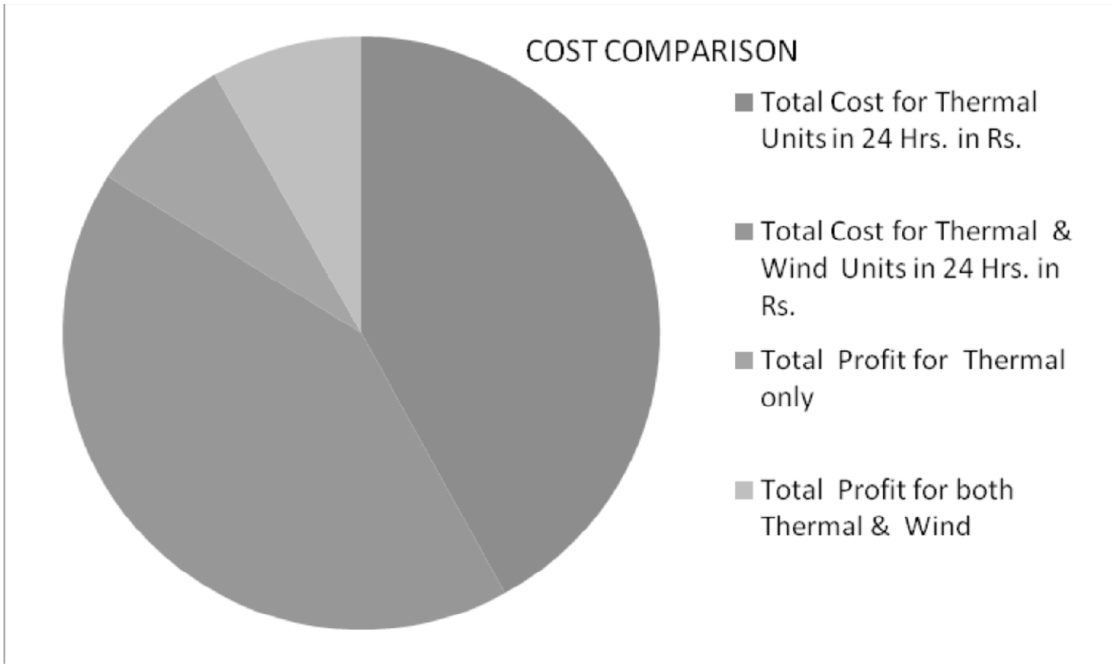
Output in terms of profit obtained (with wind)

Results are tabulated according to given data for the ten generator unit commitment problem. Here the total operating cost (Generation Cost), Selling Price per Unit & Profit Obtained is calculated.

Hrs.	*Demand (MW)*	*Rs./MWh*	*Total Cost (only for thermal) in Rs.*	*Total Cost (for thermal and wind) in Rs.*	*Cost in Rs.*	*Profit for Thermal units only in Rs.*	*Profit for both Thermal and wind In Rs.*	*Change in Profit in Rs.*	*% change in Profit*
1	700	996.75	615740.8	615740.8	697725	81984.2	81984.2	0	0
2	750	990	654952.5	654952.5	742500	87547.5	87547.5	0	0
3	850	1039.5	733585	733506.3	883575	149990	150068.7	78.7	0.052470165
4	950	1019.25	889095.6	888780.9	968287.5	79191.9	79506.6	314.7	0.397389127
5	1000	1046.25	878074.7	877444.1	1046250	168175.3	168805.9	630.6	0.374965884
6	1100	1032.75	1064712.9	1063442.1	1136025	71312.1	72582.9	1270.8	1.782025771
7	1150	1012.5	1029560.6	1027616.6	1164375	134814.4	136758.4	1944	1.441982459
8	1200	996.75	1076303.1	1073567.6	1196100	1197w96.9	122532.4	2735.5	2.283448069
9	1300	1026	1227780.9	1224331	1333800	106019.1	109469	3449.9	3.254036301
10	1400	1320.75	1309869.6	1305172.3	1849050	539180.4	543877.7	4697.3	0.871192647
11	1450	1356.75	1393141.5	1384150.6	1967288	574146	583136.9	8990.9	1.541816338
12	1500	1424.25	1474802.9	1431985.7	2136375	661572.1	704389.3	42817.2	6.472038346
13	1400	1107	1307954.8	1294569.6	1549800	241845.2	255230.4	13385.2	5.244359606
14	1300	1102.5	1178280.9	1173061.4	1433250	254969.1	260188.6	5219.5	2.047110807
15	1200	1012.5	1076303.1	1071023.4	1215000	138696.9	143976.6	5279.7	3.806646003
16	1050	1003.5	940314.8	935897	1053675	113360.2	117778	4417.8	3.897134973
17	1000	1001.25	900900.9	896490.9	1001250	100349.1	104759.1	4410	4.394658248
18	1100	992.25	983712.9	978543.2	1091475	107762.1	112931.8	5169.7	4.797326704
19	1200	999	1076303.1	1071023.4	1198800	122496.9	127776.6	5279.7	4.310068255
20	1400	1019.25	1359369.6	1353526.1	1426950	67580.4	73423.9	5843.5	8.646737812
21	1300	1039.5	1196503.4	1191324	1351350	154846.6	160026	5179.4	3.344858718
22	1100	1032.75	988934.9	983016.5	1136025	147090.1	153008.5	5918.4	4.023656249
23	900	1023.75	800787.7	796389.4	921375	120587.3	124985.6	4398.3	3.647399021
24	800	1014.75	722378	717995.7	811800	89422	93804.3	4382.3	4.900695578
		Total	24856988.1	24765927.2	29312100	4721514.5	**4830549.6**	109035	2.41498605

Comparison of total costs incurred in 24 hours and change in profit %

Total Cost for Thermal Units in 24 Hrs. in Rs.	*Total Cost for Thermal & Wind Units in 24 Hrs. in Rs.*	*Total Profit for Thermal only*	*Total Profit for both Thermal & Wind*	*Change in Profit*	*Change in Profit %*
24856988	24765927	4721515	4830549.6	109035	2.414986



Fuel cost curve

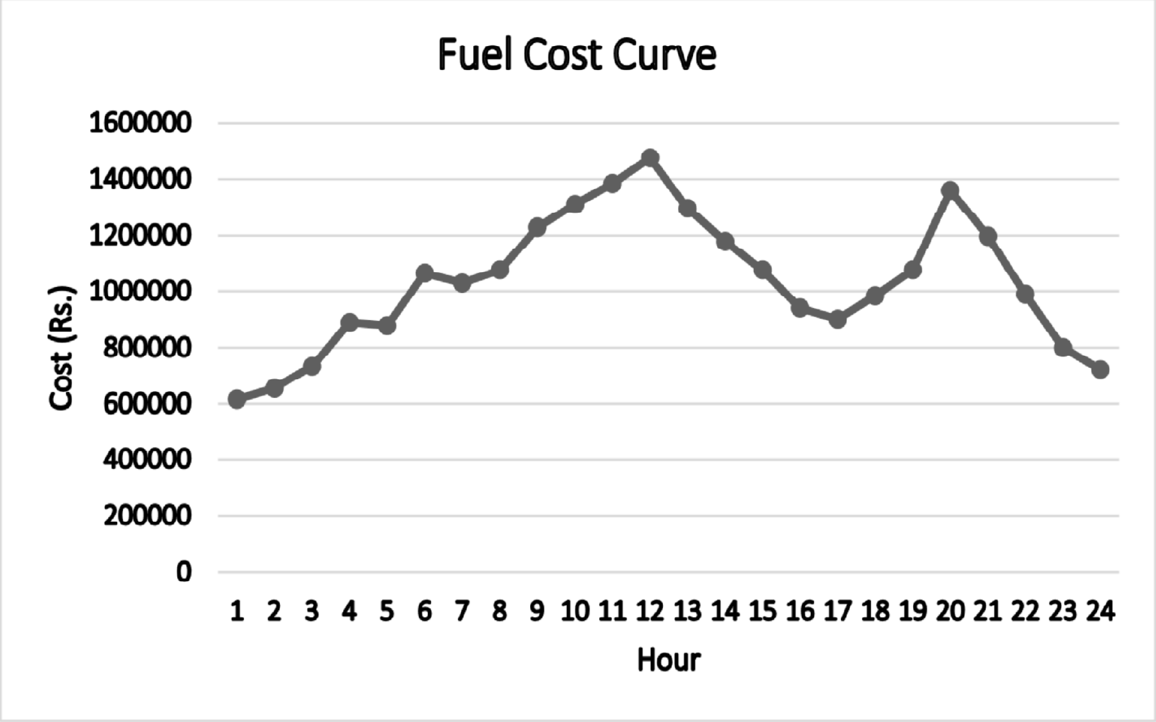


Figure 6.2: Fuel Cost Curve

CONCLUSION

It is recognized that the optimal unit commitment of thermal systems results in a great saving for electric utilities. Unit Commitment is the problem of determining the schedule of generating units' subject to device and operating constraints. The formulation of unit commitment has been discussed and the solution is obtained by classical dynamic programming method. The effectiveness of these algorithms has been tested on systems comprising four units and ten units (both with and without wind) and compared for total operating cost. It is found that the profit obtained from the unit commitment of thermal units with wind units is greater than the results obtained from using only thermal units.

SCOPE OF FUTURE WORK

This work can be further incorporated with Non-Conventional sources of energy like Solar energy, Hydro, tidal, Biomass etc. including more constraints with the Thermal Units like Ramp Constraint, Emission Constraint, Spinning Reserve Constraint, etc. Including more green energies will further reduce the costs incurred as well as emission.

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