Thermal Unit Commitment considering Pumped Storage Hydro Electricity Plants

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***Abstract*— Peak load management is one of the important challenges faced by the power industry, in terms of both frequency management and economic aspects of scheduling the generating units. Pumped storage hydro electricity (PSH) plants are the most opted plants, to act as peak load power plant, because of their quick response. When group of PSH plants are present, scheduling of each plant's operating point is necessary for handling peak/valley loads on the load curve effectively, for reducing the operating cost. PSH plants have an impact on unit commitment problem (UCP) of thermal units. By including PSH plants in the network, all the other thermal units can be operated at their best economic operating point. The optimal geographical location of PSH plants also plays a major role for economic operation. In this paper, individual scheduling of PSH plants is done, using Dynamic programming. UCP of thermal generating units is solved, considering PSH plants in network. Test results with 2 PSH plants placed in IEEE 30 bus system, over a 24-h scheduled horizon are presented. A suitable location of the PSH plants in IEEE 30 bus system is suggested.**

***Index Terms*— Economic dispatch, Peak load management, Pumped storage hydro electricity (PSH) plants, Unit commitment.**

NOMENCLATURE:

Abbreviation:

PSH	Pumped storage hydro electricity
UCP	Unit commitment problem
DP	Dynamic programming

Notations of footnote symbols:

l	Index for PSH plants
i	Index for thermal generators
t	Index for time period
p	Pumping mode of PSH plant
g	Generating mode of PSH plant
d	Lower reservoir
u	Upper reservoir
min	Lower limit
max	Upper limit

Parameters:

L	Number of PSH plants
N	Number of thermal generators
T	Number of time periods in planning horizon, with each period to be one hour
ST_i	Start up cost of i^{th} thermal generator($)
SD_i	Shut down cost of i^{th} thermal generator($)
P_{imin}	Minimum real power generation limit for generator *i* (MW)
P_{imax}	Maximum real power generation limit for generator *i* (MW)
P_i^t	Real power generated by i^{th} thermal unit in t^{th} hour (MW)
V	Water volume(m^3)
$P_{p,l}$	Total amount of electricity absorbed by l^{th} PSH unit (MW)
$P_{g,l}$	Total amount of electricity generated by l^{th} PSH unit(MW)
Ld_t	Original load at t^{th} period
Ld_m	Average load
Q	Water flow rate(m^3/s)

I. INTRODUCTION

Peak load management plays a vital role in maintaining reliable operation of a power system. Economic operation of power system is as important, as that of its reliability. Many electrical storage systems like batteries, electric vehicles, compressed air energy storage, flywheel energy storage, pumped water storage etc., are used for improving reliability and reducing operating cost of a power system. Among all the storage devices, PSH is the largest-capacity form of grid energy storage available which accounts for more than 99% of bulk storage capacity worldwide.

PSH power plants provide us a good solution to tackle with peak power demands, considering reliability and economy. They store large amounts of electrical energy during low cost off peak periods, and supplying it back to grid, during high cost peak periods. In [4] attempt was made for scheduling PSH units individually.

Unit commitment (UC) in power systems refers to the optimization problem, for determining the on/off states of generating units that minimize the operating cost for a given time horizon. It finds the best, if not, a nearly best possible solutions, which gives the minimum production cost.The solution to UC problem can be obtained using different techniques. These techniques are grouped as follows,

- Deterministic techniques
    - Dynamic programming [8].
    - Priority list [9].

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  - Integer programming [11].
  - Lagrangian relaxation [12].
  - Branch and bound method [13].
- Meta-heuristic techniques
  - Simulated annealing [14].
  - Artificial neural networks [15].
  - Fuzzy logic techniques [16].
  - Biological algorithms [10].

Dynamic programming (DP), is one of the best methods , which enumerates all the possible combinations and gives the global optimal solution.

In this paper,

a) PSH plants are dispatched, using DP, subjected to water flow limit constraints.
b) UCP of thermal units is solved, without PHS plants.
c) UCP of thermal units is solved, considering PHS plants.
d) The results of both the cases "b" and "c" compared.
e) The location of PSH in a power system is justified.

II. MATHEMATICAL MODEL

A. *Scheduling PSH plants*

Local constrains of PSH plants:

a) *Generation limit constrains:*

$$P_{p\min,l} \le P_{p,l,t} \le P_{p\max,l} \tag{1}$$

$$P_{g\min,l} \le P_{g,l,t} \le P_{g\max,l} \tag{2}$$

b) Water flow limit constrains:

$$Q_{p\min,l} \le Q_{p,l,t} \le Q_{p\max,l} \tag{3}$$

$$Q_{g\min,l} \le Q_{g,l,t} \le Q_{g\max,l} \tag{4}$$

c) Upper and lower level limits of a reservoir

$$V_{u\min,l} \le V_{u,l,t} \le V_{u\max,l} \tag{5}$$

$$V_{d\min,l} \le V_{d,l,t} \le V_{d\max,l} \tag{6}$$

d) Water balance between the upper and lower reservoir

$$V_{u,l,t+1} = V_{u,l,t} - Q_{l,t} \tag{7}$$

$$V_{d,l,t+1} = V_{d,l,t} + Q_{l,t} \tag{8}$$

State equation using hamming distance approach:

For economic operation of power systems, load factor (the ratio between average load to maximum load) should be equal to unity for ideal condition.

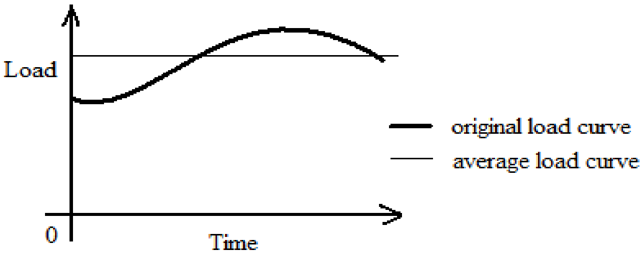

Fig.1. Original and average load curve

The objective function aims to maximize the load factor. In each period PSH plants are dispatched such that the power difference between the original load (Ld_t) and average load (Ld_m) is handled by PSH plants.

By using 'Hamming distance' definition, the following state equation is designed to accomplish the above task.

$$f(t,J) = \left| Ld_t - \sum_{l=1}^{L} P_{j,l,t} - Ld_m \right| * |\beta_t| \tag{9}$$

where, $\beta_t = \dfrac{Ld_t - Ld_m}{Ld_m}$

J is set of all possible paths in period t. β_t gives the information regarding position of Ld_t, which means whether it locates on peak or in valley positions of load curve.

With the state equation (9) the following recurrence formula is established as,

$$F^*(t,j) = Min\{F^*(t-1,j) + f(t,J)\} \tag{10}$$

$$F^*(0,j) = 0 \tag{11}$$

$F^*(t,j)$ gives the accumulated sum, from the beginning to the t^{th} period.

$F(0,j)$ =0 indicates that there is no sum, before the start of optimization.

With the use of recurrence formulae given in equations 9, 10 and 11, dispatch rates at which PSH plants are to be operated in each period is decided. By using dispatch rates, power utilized/generated by PSH plants is obtained. These details are forwarded to UCP of thermal plants. Fig.1 shows the graphical representation of original and average load curves. Modified load curve represents the total thermal load when pumped storage plants are operating. L, PSH units are dispatched such that the total load on thermal plants is reaching the average value Ld_m while satisfying the PSH plant operating constraints.

B. *Thermal UCP considering PSH plants*

The objective of UCP is to minimize operating cost, over the scheduled time horizon (e.g., 24 h) under the generator operational and spinning reserve constraints.

Mathematically, the objective function to be minimized is

$$F(P_i^t, U_{i,t}) = \sum_{t=1}^{T}\sum_{i=1}^{N} [F_i(P_i^t) + ST_{i,t}(1-U_{i,t-1})]U_{i,t} + [SD_{i,t} * U_{i,t-1}](1-U_{i,t}) \tag{12}$$

where,

$U_{i,t}$ = On/off state of i^{th} generator unit
$U_{i,t}$ = 0 when unit off
$U_{i,t}$ = 1 when unit on

$F(P_i^t)$ = Fuel cost function of the i^{th} thermal unit with generation output P_i^t, at t^{th} hour

It is a quadratic polynomial

$$F_i(P_i^t) = a_i + b_i P_i^t + c_i (P_i^t)^2 \tag{13}$$

where,

a_i = Cost coefficient of generator *i* ($/h)
b_i = Cost coefficient of generator *i* ($/MWh)
c_i = Cost coefficient of generator *i* ($/MWh^2)

System constraints:

a) *Power balance constraints*

$$\sum_{i=1}^{N} P_i^t U_{i,t} = P_{load}^t + P_{loss}^t \qquad (14)$$

P_{load}^t = Load demand at t^{th} hour

P_{loss}^t = Total transmission losses of the system, at t^{th} hour

b) *Generation limit constraints*

$$P_{i\min} \le P_i^t \le P_{i\max} \qquad (15)$$

c) *Spinning reserve constraints*

$$P_{load}^t + R^t - \sum_{i=1}^{N} P_{i\max} U_{i,t} \le 0 \qquad (16)$$

where,

R^t = Spinning reserve at hour t

In generating mode, the same cost function as that of thermal generators is considered for PSH plants also, but with zeros cost coefficients. The cost function for PSH plants, in generating mode, is given in equation (17).

$$F(P_{g,l,t}) = a_i + b_i P_{g,l,t} + c_i (P_{g,l,t})^2 \qquad (17)$$

where,

$P_{g,l,t}$ = Real power generated by l^{th} PSH plant at t^{th} hour here, a_i=0, b_i=0, c_i=0

In pumping mode, PSH plant is considered as load.

For the DP approach, we define a strategy as the transition, or path, from one state at a given hour to a state at the next hour. Number of states to search in each period, is designated by 'X'. Number of strategies to be saved at each step is designated by 'n'. *Fig.2* shows search paths in DP algorithm.

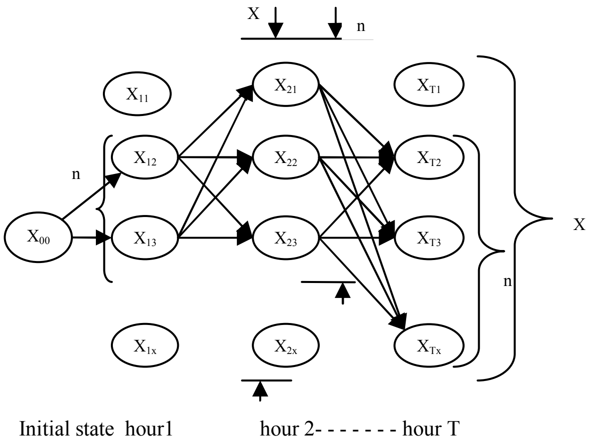

Fig.2. Search paths in UCP using DP

Mathematical model of the system is developed using SCILAB-5.3.3, which is an open source scientific software package for numerical computations.

III. COMPUTATIONAL RESULTS

2 PSH plants are dispatched, using the forecasted load curve. PSH plants are placed in IEEE 30 bus system, and UCP is solved. Details of PSH plants are taken from [4]. The load curve for 24 hour time horizon, and thermal load with PSH plants is shown in Fig.3.The average load of the system is 206.3917 MW. PSH plants are dispatched such that, the thermal load with PSH plants, approach average load.

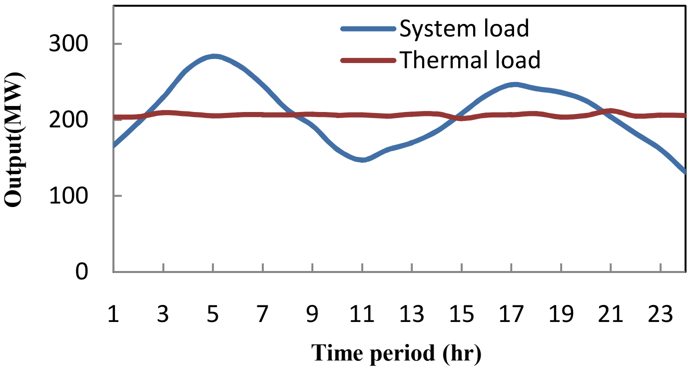

Fig. 3. System load and thermal load.

The dispatch of two PSH plants for 24 hours is shown in Fig.4. During pumping mode, power generated by the PSH plant is negative and during generation mode it is positive.

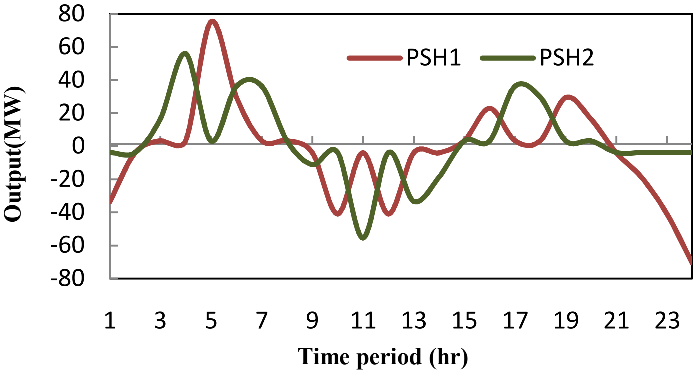

Fig.4. Dispatch of PSH units 1and2

Load factor of thermal plants, is improved from 0.728 to 0.973 when PSH plants are present in the network.

C. UCP results

UCP is solved without PSH plants. UCP is also solved with PSH plants at bus 16 and bus 24. Dispatch schedule of thermal plants, with PSH plants is given in Table II.

Production cost
without placing PSH plants in network = 13,121.362$/day
Production cost
by placing PSH plants in network = 13,010.384$/day

Savings = 110.978 $/day

The above calculation shows that, when PSH plants are present, the operating cost of thermal plants is reduced and a profit of 110.978 $/day is acquired.Table I gives the UCP solution for thermal power plant with and without PSH .

PSH plants are placed at different bus combinations, by assuming water is present at all these places, and production costs are compared. The results are given in Table III.

Table I UCP solution with and without PSH plants

Hour	System load (MW)	UC without PSH units	UC with PSH units	
			Thermal units	PSH units
1	166	111010	111110	00
2	196	111010	111110	00
3	229	111110	111110	11
4	267	111111	111110	11
5	283.4	111000	111110	11
6	272	111111	111110	11
7	246	111111	111110	11
8	213	111111	111110	11
9	192	111110	111110	00
10	161	111100	111110	00
11	147	111000	111110	00
12	160	111000	111110	00
13	170	111000	111110	00
14	185	111000	111110	00
15	208	111100	111110	11
16	232	111110	111110	11
17	246	111111	111110	11
18	241	111111	111110	11
19	236	111111	111110	11
20	225	111111	111110	11
21	204	111111	111110	00
22	182	111110	111110	00
23	161	111100	111110	00
24	131	111000	111110	00

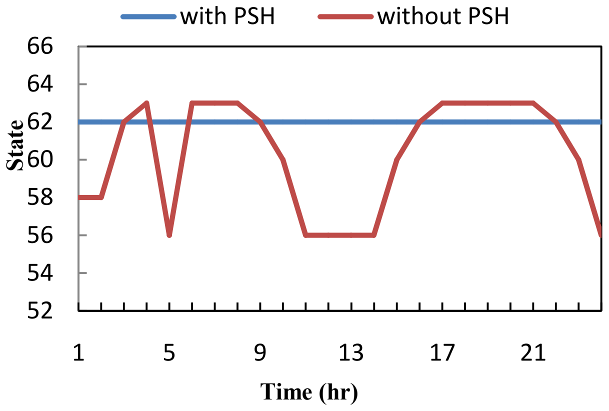

Fig.4.State (decimal form) of thermal units with and without PSH plants

From Table I and Fig.4 it can be noted that the thermal plants are not changing their operating point frequently, when PSH plants are used. The change in load is taken care by PSH plants. In table I the initial state of thermal generating units is assumed as 101010.

The economic dispatch of thermal generation units when PSH plants are placed at bus 16 and bus 24 is given in table II.

Table II Generation details of thermal and PSH plants

Period (Hour)	Thermal Units (MW)	PSH1 (Bus16) (MW)	PSH2 (Bus24) (MW)	Generation Cost ($)
1	210.45	- 33.59178	- 3.91099	532.3798
2	210.66	- 4.063417	- 3.91099	533.00748
3	216.166	3.2729537	16.393083	549.76421
4	215.41	3.2729537	55.95338	547.46702
5	215.94	75.178064	3.205466	549.05872
6	213.75	29.422912	36.17371	542.3651
7	213.32	3.2729537	36.17371	541.07567
8	213.36	3.2729537	3.205466	541.19553
9	214.40	- 4.063417	- 11.2709	544.37777
10	213.10	- 40.97304	- 3.91099	540.42903
11	216.14	- 4.063417	- 55.4304	549.7243
12	212.17	- 40.97304	- 3.91099	537.58869
13	215.45	- 4.063417	- 33.3507	547.60198
14	215.11	- 4.063417	- 18.6309	546.55142
15	207.96	3.2729537	3.205466	524.82261
16	213.14	22.885706	3.205466	540.52467
17	213.37	3.2729537	36.17371	541.22067
18	214.90	3.2729537	29.580274	545.88766
19	210.68	29.422912	3.205466	533.0337
20	212.38	16.348311	3.205466	538.20322
21	219.24	- 4.063417	- 3.91099	559.24041
22	211.46	- 18.82827	- 3.91099	535.42322
23	213.21	- 40.97304	- 3.91099	540.76066
24	214.40	- 70.49469	- 3.91099	544.38065
Operating cost				13,006.084
Transition cost				4.3
Total cost				13,010.384

PSH plants are placed at various busses. The change in operating cost and corresponding profit achieved by placing the PSH plant at various bus location pairs are calculated. The results are shown in table III.

Table III Comparison of operating cost with PSH plants at different places

PSH1 (Bus No.)	PSH2 (Bus No.)	Operating cost ($)	Profit ($)
16	24	13,010.384	110.978
3	20	12,998.143	123.219
6	22	12,983.613	137.749
9	**12**	**12,977.647**	**143.715**

Load is distributed such that, buses 9 and 12 are heavily loaded. From table III it is can be observed that, the profit varies with the location of PSH plants. The variation of profit when PSH plant is placed in heavily loaded busses and other busses is substantial. When PSH plants are placed at the heavily loaded busses (9 and 12) a maximum profit of 143.715$ is obtained. When PSH plants are placed at busses (16,24), (3,20), (6,22) the profits are 110.978$, 123.219$, 137.749$ respectively. When PSH plants are placed in heavily loaded busses the profit is higher.

IV. CONCLUSION

PSH plants are dispatched such that, the load on thermal plants is maintained near to average load. Load factor of thermal units is approached to unity when PSH are used which is an ideal condition for economic operation of the thermal plants. With PSH plants, all the thermal plants are able to operate almost at same operating point in all periods, which ensures their efficient operation. By operating PSH plants at peak and valley points on the load curve, the operating cost of thermal units is decreased. When PSH plants are placed at heavily loaded points, maximum profit of 143.715$/day is obtained. From this we can infer that, PSH plants can be constructed near heavily loaded centers, buses 9and 12, depending on availability of water.

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