OPTIMAL INVESTMENT PLANNING MODEL FOR POWER PLANTS

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Abstract. This paper deals with a computationally simple and efficient linear model developed for selecting optimum expansion plan schedule such as plants' capacities, their location, types and time of commissioning for an electric utility system over a specified planning horizon and has been tried for the most populous state of India (Uttar Pradesh) for a planning period of 10 years divided into two equal time periods each having two sub-periods i.e. rainy and non rainy. The model is essentially an economic model based on the power system network and minimizes the net present value of total annual cost. The constraints taken into account are the forecasted peak, average demands, plant size limitations, transmission losses, and seasonal variation of demand etc. In order to obtain the desired results of different time intervals of a given time span, time period indexing is also included in the model. Besides, five generation centres with three types of power plants namely thermal, hydro and nuclear or their combinations four load centres have been considered. The results obtained are furnished in the tabular forms.

1. Introduction

Electric power plays an important role in building up the national economy and has become essential not only in industrial and urban areas but for rural population also. In fact due to the uncertainties associated with future demand growth and its temporal variation, future fuel prices and long gestation periods of power projects, have made long term investment planning a challenging task. In this situation, the gains achieved from planning investments within the framework of a least cost investment model may be quite significant both in terms of economy and reliability of future power supply.

For a given utility system covering a region wherein a mix of generating plants are spatially located and connected through a transmission network to various load centers, the objective of optimal planning studies is usually to select combination of existing techniques for addition to the existing systems, determine the capacities and locations of existing and new generating plants, building up of new transmission lines, their ratings and commissioning during the planning horizon. The investment planning problem is complicated due to the time varying nature of the demand for electric power. As electricity cannot be stored except for high energy batteries, the available generating capacity of a centre at any time must be sufficient to meet the demand. It should possess some reserve capacity to meet unexpected increase in power demand.

From a typical load duration curve it is noticed that the system demand is usually close to the peak value for only 10-20% of the time. Whereas for more than half of the time the demand is close to about 50-60% of the peak demand value known as the base load. Because of this characteristic certain plants e.g. nuclear, high efficient thermal plants etc. are required to run at base load throughout the year except for the periods of scheduled maintenance. Hydel or gas turbine plants may be operated during peak demand periods only and kept idle when the system demand is below a given level.

2. Review of relevent approaches

An excellence survey of various approaches towards developing models for least cost investment planning is given by Anderson [2]. A number of optimization approaches have been attempted including marginal analysis, simulation models, dynamic programming, linear, nonlinear and mixed integer programming [2,4,5,7-14,17]. Each of them has its own advantages and shortcomings. Masse and Gibrat [9] model does not take into account generation and transmission costs. Though Bergaman's model [4] with objective function as the total cost of installation and power generation and constraints as the capacity requirements is better than the Masse model [9], yet it does not incorporate transmission costs and losses. In Narsimhan's model [11], objective function consists of fixed cost (capital cost of power plant and transmission lines) and variable costs (power generation and maintenance) but does not consider power losses, base and peak loads. Salsingikar [14] presents a model for power stations which meet the demands of load by a combination of heavy and light equipment (conventional steam & gas turbines). Objective function is the sum of capital and generation costs of both the equipments. Anyway, this model also does not incorporate transmission costs and losses. Saha et. al [13] formulates investment planning problem as a multi-divisional, multi-time period linear programming one. However, this model does not take into account upper bound on capacities, transmission costs and losses. Gosai [8] minimizes the total cost (annual fixed, generation and transmission) of the system. The constraints are the peak and average demands but there is no index for time period.

3. Present work

In the present investigation a least cost investment planning model for electric power industry is developed. The model is essentially an economic model based on the power system network in which power flows from generating centers to load centers through the proposed transmission lines. The costs of transmission and generating power together with the power losses in transmission lines are considered. Both the base and peak demands are also taken into account. In order to obtain the desired results of different time intervals of a given time span, time period indexing is accomplished. Further, sub period provision is made in the model to enable it to sense the typical daily load curve variations in different seasons of a year. Discounting costs is also exercised to find present worth of expenditure.

4.Mathematical modelling

Following assumptions are made while developing the model.

1. Railways provide sufficient coal linkages to every thermal power station location.
2. There is no atomic waste disposal problem at any nuclear power station.
3. Cost of power transmission per megawatt from generation centre to load center is directly proportional to the distance between them.
4. Power transmission losses are proportional to the length of the transmission lines.
5. Additional transmission facilities are required for evacuation of additional power to be generated by various generation centres to load centres.
6. There exists an integrated grid to which generation of all generation centres shall be fed. Power supply will also be made available by this grid to various load centres as per their demands.
7. Power can be generated in one or more than one types of the plants at each generating centre.
8. Fixed cost of any power plant is proportional to the installed capacity of the plant. This assumption is realistic because the larger size machines are installed.
9. Power generation cost is proportional to the average power generated in any plant.
10. Peak power stations can be utilized to supply base power demands but base power stations cannot be used to meet out peak load demands.

4.1 Objective function:

The objective function, z to be minimized, is the sum of the discounted annual capital, operating and transmission costs over a specified planning horizon and can be written as:

$$\text{Min } z = \sum_{i=1}^{n}\sum_{k=1}^{p}\sum_{t=1}^{q}(1+r)^{-a(t-½)}\, b_{ikt} X_{ikt} + 1/u \sum_{i=1}^{n}\sum_{k=1}^{p}\sum_{t=1}^{q}\sum_{s=1}^{u}(1+r)^{-a(t-½)}\, C'_{ikt} G'_{ikts} +$$

$$1/u \sum_{i=1}^{n}\sum_{k=1}^{p'}\sum_{t=1}^{q}\sum_{s=1}^{u}(1+r)^{-a(t-½)}\, C''_{ikt} G''_{ikts} + 1/u \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{q}\sum_{s=1}^{u}(1+r)^{-a(t-½)}\, e_{ijt} T'_{ijts}$$

$$+ 1/u \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{q}\sum_{s=1}^{u}(1+r)^{-a(t-½)}\, e_{ijt} T''_{ijts} \qquad (1)$$

4.2 Demand constraints:

Sum of the generating capacities of all the plants during a given period must be equal to or greater than the incremental peak demand of the region over the same period. However, it should be lesser than or equal to twice the incremental peak demand of the region. Mathematically:

$$2\, D_t \geq \sum_{i=1}^{n}\sum_{k=1}^{p} X_{ikt} \geq K\, D_t \qquad (2)$$

4.3 Generation centre balancing:

It requires that total base power generated from a base power station over a given period is equal to the total base power transmitted from the station to various load centres, that is:

$$\sum_{k=1}^{p} G'_{ikts} = \sum_{j=1}^{m} T'_{ijts} \qquad (3)$$

and the total peak power above the base power generated from a peak power generating station is equal to the total peak transmitted from it, that is:

$$\sum_{k=1}^{p'} G''_{ikts} = \sum_{j=1}^{m} T''_{ijts} \qquad (4)$$

4.4 Load centre balancing:

For balancing of a load centre it is necessary that total average base power received at any load centre from all other base power generating stations during a given period is equal to the average base power demand at that load centre, that is:

$$\sum_{i=1}^{n} (1- I_{ij})\, T'_{ijts} = D'_{jts} \qquad (5)$$

and total average peak power received at any load centre from all the peak power generating stations during a given period is equal to the average peak power demand at that centre. i.e.

$$\sum_{i=1}^{n} (1- I_{ij})\, T''_{ijts} = D''_{jts} \qquad (6)$$

4.5 Utilization of plant capacity:

It states that total average power generated in any plant in a time period should be lesser than or equal to the product of plant utilization factor and its capacity. It means that

$$G''_{ikts} + G''_{ikts} \leq F_{ik}\, X_{ikt} \qquad (7)$$

4.5 Upper bound on capacity:

The installed capacity of a generating centre at any location should not exceed a specified limit. This limit depends upon many factors like water resources in case of hydro power house, cooling water resources in case of thermal power house, etc. etc. Too large power generating centre at any location may turn out to be risky due to concentration of source at one place. Therefore, the total expanded capacity of any plant in all time periods or individual time period should be less than or equal to its upper limit. It means that:

$$\sum_{t=1}^{q} X_{ikt} \; ; \quad \sum_{t=1}^{q-1} X_{ikt} \; ; \quad \sum_{t=1} X_{ikt} \leq X'_{ik} \qquad (8)$$

4.6 Financial constraint:

Total investment incurred for installation of a plant during any time period should not exceed the total capital outlay available during that period.

$$\sum_{i=1}^{n} \sum_{k=1}^{p} h_{ikt}\, X_{ikt} \leq 2\, F_t \qquad (9)$$

4.7 Non-negativity restrictions:

Additional capacity, generation and transmission requirements for all location, types, time periods, sub-periods should not be less than zero. It can be expressed as:

$$X_{ikt} \; ; \; G'_{ikts} \; ; \; G''_{ikts} \; ; \; T'_{ijts} \text{ and } T''_{ijts} \geq 0 \qquad (10)$$

The various ranges considered in the above sub- paras (4.1 to 4.7) are as: i = 1, 2,……,n ; j = 1, 2, ………, m; k = 1, 2,……,p; t = 1, 2,……,q and s = 1, 2,……,u.

5. Application of the model to u.p. region of India

The proposed model is applied to Uttar Pradesh for a planning time of 10 years. The entire planning horizon is divided into two time periods i.e. 1 and 2 of first 5 years and last 5 years respectively. The unit of time period (year) is further divided into two sub-periods namely non-rainy season and rainy season. Three types of power plants, thermal, hydro and nuclear, are considered. Realizing the limitation imposed by resources availability, transportation facilities, cooling water facilities, etc., five generation centres as Obra (Thermal, Hydro); Kanpur (Thermal, Nuclear); Narora (Thermal, Hydro, Nuclear); Tanda (Thermal, Nuclear) and Ganga-Yamuna Valley (Hydro) and four load centres i.e. Obra, Lucknow, Rishikesh, Morad Nagar have been selected for the entire Uttar Pradesh. Here each of the centres represents the group of nearby centres, treating various sub regions of the state as a single centre. Transmission of power through 400 KV line is assumed.

5.1 Objective function:

Following additional assumptions are made before model is applied to U.P. region within the infrastructure of available data [1, 6, 19].

(i) Thermal and nuclear plants are used to supply base load and Hydro to meet out peak loads.
(ii) Sufficient water level in water reservoir is always available for hydro plants.
(iii) Factor of safety for reserve capacity is 1.4.
(iv) In non rainy season incremental demand is 100% of the forecasted demand [13]. During the rainy season incremental demand reduces to 65% of the forecasted demand.
(v) Peak demand is 100% that of the maximum demand in a sub-period and base demand is 60% of the peak demand.
(vi) All costs are transferred to the starting year level of the planning horizon. Further costs are same in all the sub-periods.
(vii) Financial resources are adequate.

Now writing down all the cost elements appearing in Equation -1 for Uttar Pradesh region as:

$$B_{ik} = (1+r)^{-a(t-1/2)} \cdot b_{ikt} \qquad C'_{ik} = (1+r)^{-a(t-1/2)} \cdot c'_{ikt}$$
$$C''_{ik} = (1+r)^{-a(t-1/2)} \cdot c''_{ikt} \qquad E_{ij} = (1+r)^{-a(t-1/2)} \cdot e_{ijt}$$
$$W_{ij} = (1+r)^{-a(t-1/2)} \cdot w_{ijt} \qquad C = (1+r)^{-a(t-1/2)} \cdot c_t \qquad (11)$$

In the light of the above assumptions, the optimization of the investment can be expressed as:

$$\text{Min } Z = \sum_{i=1}^{5}\sum_{k=1}^{3}\sum_{t=1}^{2} B_{ik}X_{ikt} + \sum_{i=1}^{5}\sum_{k=1}^{3}\sum_{t=1}^{2}\sum_{s=1}^{2} \tfrac{1}{2}C'_{ik}G'_{ikts} + \sum_{i=1}^{5}\sum_{k=1}^{1}\sum_{t=1}^{2}\sum_{s=1}^{2} \tfrac{1}{2}C''_{ik}G''_{ikts}$$
$$+ \sum_{i=1}^{5}\sum_{j=1}^{4}\sum_{t=1}^{2}\sum_{s=1}^{2} \tfrac{1}{2}E_{ij}T'_{ijts} + \sum_{i=1}^{5}\sum_{j=1}^{4}\sum_{t=1}^{2}\sum_{s=1}^{2} \tfrac{1}{2}E_{ij}T''_{ijts} \qquad (12)$$

Where, $E_{ij} = W_{ij} + 1_{ij}\,C$ (13)

Total number of variables in Equation (12) turns out to be 200. The various constraint as expressed in the sections 4.1 to 4.7 above can be defined for this particular application taking the values of various variables as: n = 5; p = 3; q = 2; m = 4 and u = 2. Thus, total number of constraints, except non-negativity constraints, comes out to be 128.

6. Data collected and derived

The information of data available in references [1, 6, 19] is in the forms of actual peak load met in the beginning of the planning horizon and forecasted power demands, average unit cost of power generation, estimated capital and operating costs of all the potential new facilities and length of existing / proposed transmission lines. With the help of the available data, data is generated on the following heads:
1.Demand centres and their respective forecasted base and peak demands.
2.Estimation of annual fixed and generation costs of all the potential new facilities.
3.The transmission distances, losses, efficiency and estimated annual transmission cost of proposed lines.
4.Upper Bound Capacities and Plant Utilization Factors. The following terminology is used:

Annual Fixed Cost (B_{ik}): It is the percentage amortization of capital cost and is expressed as its percentage. Considering 10% amortization (4% depreciation+ 6% interest): B_{ik} = Capital cost Rs. (lacs)perMW-Year/100

Transmission Losses (1_{ij}): If 3% losses over a transmission distance of 600 Kms. for 400 KV transmissions are considered, the transmission losses between i^{th} generation centres to j^{th} load centre are given as:

1_{ij} = 0.03 x Distance between i^{th} generation centre to j^{th} load centre/600

Annual Power Transmission Cost (W_{ij}): It we take the cost of 400 KV transmission line as Rs. 4.5 lacs per Km, the amortization of the capital cost as 10% and the maximum permissible power to be transmitted through a single transmission line as 500 MW, then W_{ij} (per MW) =4.5 x Transmission distance x 0.1 / 500

Transmission Factor (E_{ij}): This factor is expressed as: $E_{ij} = W_{ij} + 1_{ij}$. C Where, C is the annual tariff rate. If we take the composition of product mix as 35% hydro, 10% nuclear, 55% thermal, the annual tariff rate can be calculated by pooling the average costs of generation of all the types, i.e. C = (0.35x14.07+0.10x39.26+ 0.55x29.62) = 25.143 Paise/ KWH = 22.025 Rs. (lacs)/MWH

7. Results and discussion

Table - 1 exhibits the types of the plants with their location and capacities for both the time periods which may be commissioned in order to fetch maximum saving in economy. Contribution of power developed by plants at different locations towards base and peak power demands is displayed in Tables - 2. Details of base and peak powers transmitted from generating centres to various load centres can be had directly from Table - 3.

TABLE – 1: Capacity and Location of Power Plants for Different Generating Centres

Generation Centre	Incremental Capacity Location in Mw					
	First Time Period			Second Time Period		
	Thermal	Hydro	Nuclear	Thermal	Hydro	Nuclear
Obra	1217.7	328.3	--	1552.6	171.7	--
Kanpur	--	--	--	--	--	--
Narora	--	200.0	--	--	--	--
Tanda	--	--	--	--	--	--
Gangayamuna	--	2072.9	--	--	2927.1	--

TABLE – 2: Base/Peak Power Generation at Various Generation Centres in MW

A First Time Period

Generation Centre	Incremental Capacity Location in Mw					
	Sub Period-1 (Non Rainy Season)			Sub Period-2 (Rainy Season)		
	Thermal	Hydro	Nuclear	Thermal	Hydro	Nuclear
Obra	731.2/--	--/213.4	--/--	--/--	--/213.4	--/--
Kanpur	--/--	--/130.0	--/--	--/--	--/--	--/--
Narora	--/--	--/--	--/--	--/--	130.0/--	--/--
Tanda	--/--	--/--	--/--	--/--	--/--	--/--
Gangayamuna	--/--	826.9/520.0	--/--	--/--	829.5/416.5	--/--

B Second Time Period

Generation Centre	Incremental Capacity Location In Mw					
	Sub Period-1 (Non Rainy Season)			Sub Period-2 (Rainy Season)		
	Thermal	Hydro	Nuclear	Thermal	Hydro	Nuclear
Obra	931.6	--/111.6	--/--	--/--	--/111.6	--/--
Kanpur	--/--	--/--	--/--	--/--	--/--	--/--
Narora	--/--	--/--	--/--	--/--	130.0	--/--
Tanda	--/--	--/--	--/--	--/--	--/--	--/--
Gangayamuna	--/--	824.7/1078	--/--	--/--	1166.8/652.8	--/--

TABLE – 3: Base/Peak Power Transmission from Generation Centres to Load Centres (MW)

A First Time Period

Load Centre	Obra		Lucknow		Rishikesh		Moradnagar	
Generation Centre	Sub – Periods							
	1	2	1	2	1	2	1	2
Obra	508/213	--/213	223/--	--/--	--/--	--/--	--/--	--/--
Kanpur	--/--	--/--	--/--	--/--	--/--	--/--	--/--	--/--
Narora	--/130	130/--	--/--	--/--	--/--	--/--	--/--	--/--
Tanda	--/--	--/--	--/--	--/--	--/--	--/--	--/--	--/--
G. Yamuna	--/--	216/7	--/151	147/98	300/201	195/131	526/168	271/180

B Second Time Period

Load Centre	Obra		Lucknow		Rishikesh		Moradnagar	
Generation Centre	Sub – Periods							
	1	2	1	2	1	2	1	2
Obra	614/112	--/112	267/--	--/--	--/--	--/--	50	--/--
Kanpur	--/--	--/--	--/--	--/--	--/--	--/--	--/--	--/--
Narora	--/--	130/--	--/--	--/--	--/--	--/--	--/--	--/--
Tanda	--/--	--/--	--/--	--/--	--/--	--/--	--/--	--/--
G. Yamuna	--/315	422/163	--/180	176/117	364/343	237/158	461/340	332/221

7.1 Feasible plant locations

Thermal power plant of capacity 1217.7 MW is obtained at Obra only for the first time period. During the second time period the plant capacity is 1552.6 (Table – 1). At all other locations thermal plant is seen not to be feasible. However, for the other power plant locations the advantage of low power cost due to comparatively reduced transmission cost to nearby load centres is not noticed. Obra has the advantage of low power generation cost over high transmission cost to meet power demand of its own and distant load centres.

Hydro plants are obtained at Obra of 328.3 MW capacity, at Narora of 200 MW capacity and at Ganga-Yamuna Valley of capacity 2072.9 MW during the first time period and for second time period, plants of 171.7 and 2927.1 MW capacities at Obra and Ganga Yamuna Valley, respectively (Table-1). These plants would satisfy power demands of all nearby and distant load centres. Further, in case of hydro plants the effect of high transmission cost associated with the power transmission to distant load centres on the total cost is not observed. Nuclear plants are found infeasible for both the time periods, Table -1.

7.2 Generation and load centres

Tables 1-3 reveal that power plants met local demands almost completely but partially the demands of the nearby load centres and afterwards, they meet the demands of far situated load centres.

7.3 Base & peak power generation with seasonal effects

During a non-rainy season, base demands are met with the power generation of both the thermal and hydro plants. Whereas, in rainy season, hydro plants will satisfy the base as well as peak demands, Tables – 2. The reason being that in rainy season, demand reduces and the generation of hydro plants, which is the cheapest, is sufficient to meet out both the peak and base power demands. This looks to be a better planning as under rainy season, annual overhauling of thermal power stations can be done without any difficulty to improve its efficiency for non-rainy seasons. It is worthwhile to mention that during first time period the base demand of Obra region in non-rainy season is met by its own thermal generation while in rainy season it would have power from Narora and GangaYamuna Valley. Peak demand of this region is satisfied by its own and Narora's generation in non-rainy season. While, for rainy season it draws a little power from GangaYamuna Valley in addition to its own generation.

7.4 Dependency of plants:

It is observed from Tables 1 to 3 that as soon as the resources of power generation are utilized at proposed generation centres in a time period, the new power plants are found at far distances from the load centres to meet out incremental demands during the next time period. For example during first time period hydro plants of 328.3 MW and 200 MW capacities are required at Obra and Narora, respectively. But, during second time period hydro plant of capacity 171.7 MW only would be enough at Obra due to utilization of water resources in the previous time period. Hence, to meet out demand of Obra load centre in second time period its dependency is increasing at GangaYamuna Valley

8. Concluding remark

Almost all the generating centres are found near to the major load centres. Thermal power plants are also observed near the coal resources. It is because of the reason that transmission cost to distant load centres would turn out to be higher and generation cost would be so much reduced as to keep total power cost to the minimum. In case of hydro plants its generated power meets out demands of all the load centres. Of course, demand of the load centre situated near the plant shall be satisfied first in comparison to the far off load centres.

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Nomenclature

A	Time units in a time period i.e. length of time period
b_{ikt}	Annual fixed cost of i^{th} generation centre of k^{th} type to be installed in time period 't' (Lacs/MW-Year)
B_{ik}	Discounted annual fixed cost of i^{th} generation centre of k^{th} type (Lacs/MW-Year)
c'_{ikt}	Annual base power generation of i^{th} generation centre of k^{th} type during time period't' (Lacs/MW-Year).
C'_{ik}	Discounted annual base power generation cost of i^{th} generation centre of k^{th} type (Lacs/MW-Year)
C''_{ikt}	Annual peak power generation cost of i^{th} generation centre of k^{th} type during period 't' (Lacs/MW-Year)
C''_{ik}	Discounted annual peak power generation cost of i^{th} generation centre of k^{th} type (Lacs/MW-Year)
C_t, C	Annual tariff rate during time period 't' (Lacs/MW-Year)and Discounted annual tariff rate (Lacs/MW-Year)
D_t	Incremental peak demand in time period 't'
E_{ijt}	Annual power transmission cost from i^{th} generation centre to j^{th} load centre after taking loses in power transmission into account during time period 't' (Lacs/MW-Year)
E_{ij}	Discounted annual power transmission cost from i^{th} generation centre of j^{th} load centre after taking losses in power transmission into account (Lacs/MW-Year)
D'_{jts}	Average incremental base power demand of j^{th} load centre in time period 't' and sub period 's'
D''_{jts}	Avg. incremental peak power demand over base power demand of j^{th} load centre in time 't', subperiod 's'
F_{ik} , F_t	Plant utilization factor of i^{th} plant of k^{th} type and Total outlay available during time period 't'
G'_{ikts}	Average incremental base power generation of i^{th} plant of k^{th} type in time period 't' and sub period 's' (MW).
G''_{ikts}	Average incremental peak power generation over and above base power generation of i^{th} plant of k^{th} type during time period 't' and sub period 's' (MW).
h_{ikt}	Investment per unit installed capacity for i^{th} plant of k^{th} type in time period 't'
I, j, k	Indices for generation centre, load centre and type of plant, respectively
1_{ij}	Line losses during power transmission between i^{th} generation centre and j^{th} load centre
M,n,p	Numbers of load centre, generation centre and types of plants, respectively
p'	Number of types of plants which can be used as peak plants
Q, U	Number of time periods and Number of sub periods in a unit of time period
S, T	Indexes for sub period (varies from 1 to u) and time period (varies from 1 to q)
T'_{ijts}	Avg. annual base power transmitted from i^{th} generation centre of j^{th} load centre in time 't', subperiod 's' (MW)
T''_{ijts}	Average annual peak power over and above base power transmitted from i^{th} generation centre to j^{th} load centre during time period 't' and sub period 's' (MW)
w_{ijt}	Average annual power transmission cost from i^{th} generation centre to j^{th} load centre in time period 't' without considering power losses (Lacs/MW-Year)
w_{ij}	Discounted average annual power transmission cost from i^{th} generation centre to j^{th} load centre with considering power losses (Lacs/MW-Year)
X_{ikt}	Incremental capacity of i^{th} plant of k^{th} type to be installed in time period 't'
X'_{ik}	Upper bound on capacity of i^{th} plant of k^{th} type.