T. R. NO. 60

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Technical Report

A NETWORK PROGRAMMING APPROACH FOR INVESTMENT PLANNING IN ELECTRIC POWER SYSTEMS : CASE STUDY FOR NORTHERN REGION OF INDIA

by

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WP 1974/60

INDIAN INSTITUTE OF MANAGEMENT
AHMEDABAD

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Technical Report

Title of the report A Network Programming Approach for Investment Planning in Electric Power Systems : Case Study for Northern Region of India

Name of the Author Shishir K. Mukherjee.

Under which area do you like to be classified? OPERATIONS RESEARCH: POWER SYSTEMS ~~ESTIMATES~~

ABSTRACT (within 250 words)

The purpose of this paper is to describe a Network Programming Model for least-cost investment in electric power generation and transmission system and illustrate it by a case study involving application of this model to northern Region of India for planning the electric power generation and transmission system network to meet projected peak demand at the end of Vth Plan Period. ~~in the year 1978-79.~~ The model described in this paper is essentially an economic model based on the power system network in which electric power flows from generating nodes to load centres through existing or proposed transmission lines and costs of generation of power and transmission including power and energy losses are accounted for. The model with the aid of a network computer programme obtains a least-cost flow pattern in the networkwhich determines the optimal investments in generating plants and transmission network. The optimal solution obtained should be tested with lead flow studies to determine system relaibility under various contingencies as is done in case of any other modelling approach.

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Date August 28, 1974.

Nov 27. 1974

Shishir K. Mukherjee
Signature of the Author

A Network Programming Approach for Investment Planning in Electric Power Systems : Case Study for Northern Region of India

Shishir K. Mukherjee

1. INTRODUCTION:

Electric power now plays a crucial role in the development of an economy. Availability of adequate electric power has now become essential not only in industrial and urban areas but the rural society is also getting dependent on the use of electricity for agricultural and other needs. Due to the high rate of demand growth for electricity and prohibitive costs of shortages, investment planning in electric power generation and transmission systems has received increasing attention during the last two decades. Whereas uncertainties regarding future demand growth and its temporal variation, technological innovations in the power generation and transmission field, future fuel prices and long gestation periods of power projects make long term investment planning a challenging task, the gains from planning investments within the framework of a least-cost investment planning model can be quite considerable both in terms of economy and reliability of future power supply. As in most countries the power system has been transformed from isolated generation and consumption centres with small generating plants to interconnected regional or national systems consisting of fairly large generating plants and high voltage transmission lines, the need for planning additional investments within the context of a systems study has become obvious.

An excellent survey of various approaches towards developing models for least-cost investment planning beginning with the pioneering work at Electricite' de France is given by Anderson.[1] Various approaches at optimization has been attempted including marginal analysis, simultation models, dynamic programming, linear, non-linear and mixed-integer programming.[1,5,6,8] The concentration in most of the studies has been towards optimal choice of type (i.e. hydro, thermal and nuclear), capacity and time-phasing of generating plants, with little or no consideration regarding the planning of the transmission networks. Thus the studies were mostly single-area studies and neglected transmission between various generating plants and between generating plants and load centres. There has been a few studies [5,6] where multi-region models were considered with transmission lines joining various regions but still neglecting transmission within the region. The author has no knowledge of any study which considered an existing or proposed power network in its totality with various generating plants and load centres interconnected by a transmission network within the framework of an investment model for planning future investments in generation and transmission system. However, transmission networks have been explicitly considered in load-flow studies which are undertaken to determine the actual voltages and currents and the corresponding phase angles in an electrical network given certain power inputs and outputs at the various nodes. Load flow studies are useful as they simulate the behaviour of a particular power system under normal conditions and under various contingencies induced by the outage of generating plants and transmission lines and give valuable information regarding system reliability. Load flow studies involve the solution of a set of non-linear A.C. flow equations and no optimization in terms of generating plants or transmission lines could be attempted through load flow studies. However, they could be useful in comparing system reliability under various contingencies of alternative power system designs where economic or least-cost studies have already been carried out.

The purpose of this paper is to describe a Network Programming Model for least-cost investment in electric power generation and transmission system and illustrate it by a case study involving application of this model to Northern Region of India for planning the electric power generation and transmission system network to meet projected peak demand in the year 1978-79. The model described in this paper is essentially an economic model based on the power system network in which electric power flows from generating nodes to load centres through existing or proposed transmission lines and costs of generation of power and transmission including power and energy losses are accounted for. The model with the aid of a network computer programme obtains a least-cost flow pattern in the network which determines the optimal investments in generating plants and transmission network. The optimal solution obtained should be tested with load flow studies to determine system reliability under various contingencies as is done in case of any other modelling approach.

2. INVESTMENT PLANNING IN ELECTRIC POWER SYSTEMS

Given an existing power system for a region containing a mix of generating plants spatially located and connected through a transmission network to load centres, and its demand growth pattern over a given planning horizon, the purpose of optimal investment planning studies is to attempt answering the following questions:

1. What combination of available technology (out of thermal, hydel) should be selected for addition to the system to meet the increasing load,
2. What should be the capacity of these generating plants when different sizes are available with possible economies-of-scale,
3. Where should these new plants be located among alternative sites,
4. Which additional transmission lines should be built,
5. What should be the kv-rating of the new transmission links, and
6. When during the planning horizon should these generating plants and transmission lines be commissioned?

The model described in this paper attempts to answer the first five questions listed above while minimizing the overall system cost. Additions to generation and transmission system are planned to meet the projected demand at the end of the planning horizon with the assumption that system additions are made at appropriate times during the planning horizon to keep pace with the growing demand. In this sense the model is a static one as it does not answer the scheduling problem during the planning horizon on the last question in the above list. A dynamic model could be formulated wherein the planning horizon is divided into a number of periods and optimal scheduling of generation and transmission projects are obtained as the solution of the model.[5,6]

The investment planning problem is complicated due to the time-varying nature of the demand for electricity. As electricity cannot be stored except through a pumped storage hydel plant or high energy batteries, the generating capacity available at any time must be adequate to meet the demand and also provide some reserve capacity to meet situations of forced outage of one or more of the generating plants (usually of the largest unit) or unexpected increases in power demand. The variation of power demand during a year is usually expressed through a load duration curve which gives the percentage of total time during the year the demand is expected to exceed any given value of demand. The demand for a load centre is usually given as its peak demand. In a typical load duration curve, it is usually observed that the system demand is close to the peak value for only about 10-20% of the time whereas for more than half the time the demand is nearer to about 50% of the peak demand value known as base load.

Because of this characteristic of system demand certain plants would run at base load throughout the year except during periods of planned maintenance. Usually nuclear plants and highly efficient new thermal plants fall under this category. Certain other plants such as hydel plants (with reservoir) or gas turbine plants may be operated so that they only run during peak demand periods and remain idle when the system demand is below a given level. It is thus expected that if a power system has enough capacity to meet the peak demand, it will have sufficient capacity to meet power demand throughout the year as planned maintenance of generating plants could be scheduled during off-peak seasons. In this paper the peak demand is used as the basis for investment planning in generating capacity. This approximation may be justified if proper consideration is given to the maximum energy availability and actual hours of operation of generating plants of different types such as hydel plants, new or old thermal plants and nuclear plants. It is assumed here that once the investments in various generating units are decided this way by making assumptions regarding annual operating hours of various plants and then minimizing annual costs of operation and capital charges. Operational planning optimizatio models would be used to schedule operation and maintenance of available generating units in an optimal fashion to minimise the operating cost.

A satisfactory way of dealing with the varying demand as specified by a load duration curve would be to partition it into several discrete ranges each corresponding to a step in the demand curve and plan so that adequate generating capacity is available for each step of the load duration curve.[8] A simplified approach where the load duration curve is divided into three steps is used for a study in Mexico.[9] However, these models are linear or mixed integer programming models concentrating on generation. Though it would be possible to introduce such sophistication in network models also, this is beyond the scope of the present paper as this will increase the size of the network tremendously to consider generation as well as transmission within the same model. As worst conditions are usually faced during the peak demand, the power generation and transmission system is studied under peak demand conditions and appropriate load factor is used to make adjustments for variation in demand during off-peak seasons specifically while computing annual operating cost and transmission losses.

One of the basic decisions in investment planning is the choice of technique for generation among hydel, thermal and nuclear plants. Straight-forward economic comparisons are usually not possible as different plants may have different availability, energy capability and cost characteristics. Specifically hydel plants create certain difficulties as only a fraction of the total installed capacity of a hydel plant may be available during peak season and the total energy availability would be limited by the size of the reservoir and annual inflow. Thus appropriate adjustments are needed. Credit is given only for firm capacity of a hydel plant available during the peak season and its capital charges per megawatt could also be adjusted to reflect the average number of hours the plant could be operated during the year due to total energy availability constraint. Thermal and nuclear plants would usually be available when needed except during periods of planned maintenance.

As discussed earlier system reliability considerations are not included as a part of the optimal investment network model as load flow studies will have to be carried out after the preliminary system design is completed. However, the effect on the power system of outage of one or more plants or transmission lines in terms of overloading and changed power flow could be studied using this model by incorporating the necessary changes in the system network. Similarly schedule could be determined by using reduced demands at load centres and considering non-availability of generating plants undergoing scheduled maintenance.

3. NETWORK MODEL FORMULATION

A power system could be easily visualized as a network consisting of a set of nodes denoting spatially dispersed generating plants and load centres linked together by arcs which denote the transmission lines. For the investment planning network model we do not propose to include the power distribution network. The load centres included in the power network referred to the points where transformers reduce voltage for distribution over an area. The load at a particular node is equal to the consumption within that area plus the distribution losses. It should be noted that optimal distribution network design is also a network optimisation problem and can be handled using similar modelling approach.

The power system network described above consisting of generating plants and load centres as nodes and transmission lines as arcs will be augmented by the addition of conceptual nodes and arcs, which do not occur in the physical network, for our model formulation. One specific node S, called the source node will be added and this will be connected to all nodes, representing existing as well as proposed generating plants by a set of conceptual arcs to be called generation arcs. Similarly another specific node D, called the demand node will be added and all nodes representing load centres will be connected to the demand node by conceptual arcs to be called consumption arcs. It could be conceived as if all power is being generated at the source nodes and flows through the generation nodes and the transmission network to be finally consumed at the demand node after passing through the load centres.

Thus, in the augmented network, we have a generation arc corresponding to each existing or proposed generating plants and flow in a generation arc corresponds to generation of a certain amount of power in megawatts in the generating plant. Similarly, corresponding to each load centre there is a consumption arc and any flow in these arcs represent the consumption of electricity at the load centres. In addition each transmission line is represented by one arc joining two nodes which could be generating plants, load centres or junction points where two or more transmission lines meet. Transmission lines in which the direction of power flow is not specified and it is possible for power to flow in either direction are represented by a pair of arcs oriented in opposite directions so that model solution will indicate the direction of power flow. By convention all arcs in the model network are directed and flow can take place in an arc only along the orientation of the arc. The orientation of an arc is specified by the order of the nodes at its extremities and flow takes place from the initial to the terminal node.

Each arc in the model network is associated with three other parameters: lower and upper bounds on arc flow which should not be violated and unit cost of flow in the arc, being the cost of sending one megawatt of power through an arc of the network. Total cost of flow through an arc could be a nonlinear function of the flow in the arc specifically for transmission arcs due to nonlinear power losses and also generation arcs if economies-of-scale are present, but for the time being we observe that the costs are linear. Nonlinear costs function described later in the paper can be handled by solving the network model in an iterative fashion. The bounds on flow and unit cost of flow in specific arcs of the network are judiciously specified so that the model network gives a realistic representation of the system constraints and costs.

Each generation arc has lower bound of zero, upper bound equal to the maximum available capacity of power generation in megawatts (MW) and unit cost of flow given by the cost of operating one unit (MW) of generating capacity for one year at appropriate load factor. Consumption arcs have both lower and upper bounds equal to the peak demand and unit cost of flow as zero. Revenue for electric energy sold could also be considered in the model by defining appropriate negative unit costs in these arcs and defining upper bound of flow as the maximum amount of power that could be sold. The capacities of the transmission lines determine the upper bounds on transmission arcs, the lower bound being zero. Unit costs of flow equals costs of installation (for proposed lines only) per MW and cost of power losses.

The constraints of the network model and the objective or criterion function to be minimized can now be expressed by mathematical relationships for a given power system. Let there be m generating plants, n load centres and p junction nodes in the network in addition to the source node S and demand node D. We define the following notations:

f_{Si} = Power generated by ith generating plant, MW, $i = 1,2, \ldots, m$.

f_{jD} = Power consumed by jth load centre, MW, $j = 1,2, \ldots, n$.

f_{ij} = Power flow in transmission line (i, j), where node i and node j are connected by a directed arc, $i, j \neq S; i, j \neq D$.

U_{ij} = Upper bound on flow in transmission arc (i, j).

C_i = Unit cost of power generation at ith generating plant per MW, i = 1,2 ..., n.

d_{ij} = Unit cost of power transmission through transmission line (i, j); $i, j \neq S; i, j \neq D$.

P_i = Available capacity of ith generating plant during peak period, MW.

L_j = Peak demand at jth load centre, MW.

The following constraints must be satisfied by any flow soluti to the model network:

Generating capacity constraints : $0 \leq f_{Si} \leq P_i$, i = 1,2,...,

Load constraints : $L_j \leq f_{jD} \leq L_j$, j = 1,2,..,

Transmission capacity Constraings : $0 \leq f_{ij} \leq U_{ij}$; $i, j \neq S$;

$i, j \neq D$

Subject to the above constraints the objective function (TC) corresponding to the total generation and transmission cost in the network has to be minimized:

$$\text{Minimize TC} = \sum_{i=1}^{m} f_{Si} \; C_i + \sum_{\substack{\text{all}\\ \text{transmission arcs}\\ (i,j)}} f_{ij} \; d_{ij}$$

A solution of the network model expressed as a set of flows in the arcs which satisfies constraints (1) - (3) and minimizes the objective function (4) is termed as an optimal solution and representa a design of the system network which specifies the optimal capacities of the various generating plants and an optimal flow distribution in the transmission network. This is an optimal choice.

based on annual cost of operation between a set of existing and proposed plants at different locations and between a set of existing and proposed transmission links. As the generating plants can run at any capacity below their rated installed capacity in the optimal solution, this represents a decision regarding the optimal capacity of proposed plants and retirement of existing plants. Similarly, the KV ratings of transmission lines could be determined from the optimal solution based on the flow in a transmission line.

The optimization of model network described by (1) - (4) is a linear programming problem and optimal solution can be obtained by using Simplex method[3] for which standard computer routines are available. However, the network structure of the problem makes it amenable to a simpler and much faster network flow solution procedure described by Ford and Fulkerson[4] as 'Out-of-Kilter' algorithm. As described later the solution procedure may have to be judiciously applied in an iterative manner if nonlinear cost functions are encountered.

4. APPLICATION OF NETWORK MODEL TO NORTHERN POWER REGION OF INDIA

For the purpose of coordinated development and operation of electric power system in India, the country is divided into five power regions which, it is expected, will be later integrated into a national power grid. Northern region includes the states of Jammu & Kashmir, Punjab, Haryana, Rajasthan, Uttar Pradesh, Himachal Pradesh and Union Territory of Delhi. In this section, the network model described above has been applied to the Northern Region of India for designing the optimal power generation and transmission system to meet the system load at the end of the fifth five year plan period(1978-79). As generating plants usually take 5-8 years for installation, system planning should be done sufficiently in advance for an horizon of 10-15 years or more. Decision on any generating plant to be installed before 1978-79 must have been taken by now and this study can only illustrate the approach to be taken for future five year plans. As reliable data on load centre-wise demands or project proposals on generating plants and transmission lines were not available for the sixth plan period or beyond, this study was limited to the fifth five year plan period.

The annual peak demand for electricity at various load centres in Northern Region for the year 1978-79 is shown in Table 1. These demand figures correspond closely to the Northern Region demand as used by Shiralkar and Parikh[9] and earlier in a study[2] carried out by the Department of Atomic Energy with the States concerned and reported in Atomic Energy Commission Monograph 2.

To meet the gap between the existing capacity and peak demand for 1978-79, several project proposals for new generating plants were considered. A list of existing as well as proposed generating plants is shown in Table 2. The transmission system need augmentation by the addition of new links and by strengthening the existing ones wherever necessary to carry the increased power load and to connect new generating stations to the network. Several new 400 KV single circuit lines were also proposed to interconnect major generating stations, reduce transmission losses and to improve the reliability of the system. A list of existing as well as proposed transmission lines with their KV ratings is given in Table 3.

Only 132 KV, 220 KV and 400 KV transmission lines have been considered to be included in the transmission systems. For transmission lines with lower KV rating the demands were grouped with the transmission like of higher KV rating to which they were connected. Some lumping of load was also done at some load centres specially where there was only one transmission line leading to a load centre which had no alternative route of receiving power. The demand considered for each load centre was annual pe demand in 78-79 expected to occur during working days of the week in summer months.

It was observed that in many cases more than one generating plants were located at the same place as in Obra, Kanpur, Delhi etc. These locations were defined as generating regions and an additional node was assigned to each of these regions where generated electricity from all the plants flows in for further transmission to the load centres. Some of the generating regions were also load centres, as they were at the same location i.e. Kanpur, Delhi etc. In these situations separate nodes in the network were defined to represent generating regions and load centres and these were connected with high-capacity transmission arcs with zero or very low unit cost of flow in these arcs.

The capacity of power transmission of a transmission line is limited by its KV rating and the conductor size. The transmission lines could be occasionally loaded till their thermal limit is reached but this usually increases the powerloss and it may be better to switch to a higher KV rating or add additional circuits once the load exceeds a certain limit. On the other hand, it may not be economical to transmit power lower than a minimum value through a transmission line of a certain KV rating as it would be better to employ a line of lower capacity to advantage. Table 4 shows the ranges assumed for transmission lines of different KV ratings. Their capital costs, conductor size and K factor(to be discussed later), where SC and DC respectively denote single circuit and double circuit lines.

In the network model the higher values of the ranges were used as upper bounds on the transmission arcs and lower bounds were fixed at zero. If flow in any proposed transmission arc was below the recommended range then a transmission line of lower KV rating would be recommended unless there are other considerations such as system reliability or future demand growth to justify a transmission line of higher KV rating.

Cost of Generation: Cost of generation at a power plant has two components - fixed and variable charges. The fixed annual charges include interest on capital depreciation, insurance and fixed charges due to maintenance. The variable charges are the operating costs and consist of mainly the fuel cost. The annual variable costs depend on the energy generated i.e. the power capacity multiplied by the hours of operation during the year.

Different assumptions have been made for the existing and proposed plants regarding their costs of generation. Thermal and hydel plants on which construction work has begun or is about to begin soon has been assumed to be ready for power generation in 1978-79 are treated as existing plants. All the other plant proposals for which sanction has not been given are considered as proposed plants. Many new plants and extensions to existing plants have been proposed all of which need not come up during the fifth plan. Among the proposed plants a nuclear generating unit at four proposed locations, Narora, Matatila, Rupar and RAPP were considered. Subsequently Narora has been chosen as the location for this plant and other locations were dropped from the model. However the proposed nuclear plant at Narora may not be commissioned by 1978-79.

In case of existing plants the capital cost is a sunk cost and hence it is not considered. Cost of generation for existing plants include fuel cost and only 2.5% of their capital cost as annual maintenance charges. For the proposed plants, the cost of generation includes fuel cost and annual charge of 12.5% of the capital cost (this consists of 6% interest charges, 4% for depreciation and insurance and 2.5% for maintenance charges). This cost differential between existing and proposed plants will ensure that in the network model solution the existing plants will be utilized to their installed capacity before proposed plants are called in. Only in the case of old thermal plants of very low efficiency and high operating costs, the model might recommend their retirement.

The distinction between existing and proposed plants made during this study may not be perfect now as some of the proposed plants have already been sanctioned or are being constructed so that decision regarding them has been taken whereas commissioning of some of the plants termed as existing may be delayed due to various reasons. The capital costs of generating plants, specially of hydel plants also have a tendency to rise much higher than the initial estimate as they get delayed. These difficulties should not be there if sufficiently long term planning of power systems is resorted to and a well defined set of project proposals are prepared at least 10-15 years in advance of the target year so that optimal choice can be made among the various alternatives.

Cost of Transmission

As in the case of cost of generation, the annual cost of transmission also has fixed and variable components. The fixed costs are due to annual capital charges (interest, depreciation etc.) and the variable costs are due to power and energy losses during transmission. To counteract the power loss additional capacity must be commissioned and the costs of this can be ascertained. Similarly, the energy losses could be priced to obtain a monetary value. Both these costs have been more or less standardized for 132 KV SC/DC, 220 KV SC/DC and 400 KV SC lines and for the same line they are directly proportional to the length in KM. Again a distinction is made between the existing and proposed transmission lines and no capital charges are shown against existing lines. Given the KV rating and the number of circuits for a transmission line, the amount of power in megawatts that can be economically and safely transmitted is given by a range as described earlier. If the amount of power to be transmitted is known, then transmission costs per megawatt can be computed as in the case of generating plants. whereas the variable operating costs due to fuel costs are approximately linear for generating plants, the cost due to power losses is a nonlinear function of power transmitted and is proportional to the square of power transmitted in megawatts. The nonlinearity of the power loss function creates some difficulties in the network model for existing transmission lines. However for proposed lines though the annual cost of capital charges per megawatt (a decreasing function of the amount of power transmitted in MW) and the annual cost of power losses per megawatt (an increasing function of the amount of power transmitted, in MW) are both nonlinear functions the resulting total cost of power transmission per megawatt is reasonably linear for a wide range near the transmission capacity of the line. Within this range, the cost of transmission for proposed lines could be taken as linear. These costs have been computed following the assumptions given below and are listed in Table 5. As Table 5 shows, for existing lines an average unit cost is used for a range and based on the actual power flow in the transmission line this unit cost value can be corrected in an iterative fashion.

The power loss in Watts (only I^2R loss is considered, where I is the current per phase in amperes and R is the resistance of the line in ohms) in a transmission line is given by the expression: Power loss = P^2KD watts .... (5).

where P = Power transmitted in MW

D = Distance of the transmission line in KM

K = a multiplying factor equal to the power loss in watts when one MW of power is transmitted through one KM. K depends on the KV rating, number of circuits and the conductor size of the transmission line. Typical values of K for various KV ratings are shown in Table 4 for which a power factor of 0.8 was assumed.

For computing the annual energy loss in a transmission line a load factor of 0.6 was assumed. The load loss factor corresponding to this is 0.432 when peak demand is used for computing the energy losses. Thus annual energy loss in MWHr is given by the expression:

$$\text{Annual energy loss} = P^2 K\, D \times 0.432 \times 876 \times 10^{-6}$$

When P megawatts are transmitted through D kilometers in MWhr .... (6)

Thus Annual energy loss / km / MW transmitted

$$= 0.00378 \ PK \ \text{MWhr} \quad \ldots \quad (7)$$

$$= \text{Rs. } 0.378 \ PK \ \text{using a price of}$$

Rs. 100/ MWHr as the price of energy.

It is seen that the unit cost due to energy losses is not constant for a given transmission line with known value of K, but is all dependent on the generation of power transmitted in megawatts.

We can also define 'Efficiency' η of a transmission line as the ratio of power received to power sent out or the fraction of power received. The efficiency is given by the relation

$$\text{Efficiency, } \eta = \frac{P - P^2KD \cdot 10^{-6}}{P} = 1 - PKD.10^{-6} \quad \ldots\ldots \quad (8)$$

where P, K and D have the same meaning as defined before.

An optimal solution of the network model specifies a distribution of power flow in the transmission network. From this data the efficiency of the transmission lines and power loss in them could be easily computed. The optimum solution could be corrected by either generating additional power at the generating nodes to counteract the power loss or augmenting demand at each load centre by the amount of power loss in transmission from the generating node and obtaining a new solution with the augment values of demands. Thus power generated in the system could be computed in an iterative fashion to provide for the power lost in the system in addition to the demands at the load centres and this method of computation should converge quickly. An alternative way of accommodating power losses due to transmission in a network model is to use a special kind of network formulation known as 'networks with gains'[7] where multipliers are defined in arcs which changes the flow through an arc by a nonzero multiplying factor Kij which could be greater or less than one to represent gain or loss of flow through the arc.

Computer Runs and Analysis for the Northern Region

From the available data on the existing and proposed generating plants, existing and proposed transmission lines, capital and operating costs and demand for power at various load centres of Northern Electricity Region, the conceptual network was constructed following the procedure described in Section 3. The generating plants were grouped into 18 generating regions each represented by a node, whereas the load centres were grouped into 43 nodes. There were 100 transmission lines (existing and proposed) and the conceptual network for the investment planning model consisted of 259 arcs, some of which were needed to satisfy various system constraints and characteristics of generating and transmission system.

The network model was solved by using NETFLW code, a version of Ford and Fulkerson's 'out-of-Kilter' algorithm in IBM 360/44 computing system and each run took approximately 1.50 minutes of computer time. Starting solution was provided by assigning initial flow values in all the arcs of the network which were judiciously chosen based on the knowledge of the power system and satisfying flow conservation (flow into a node = flow out) at each node of the network. Six computer runs were made as described below to systematically improve the accuracy of the model and to obtain solutions under alternative assumptions regarding the available capacity of hydel plants during system peak demand. The generation schedule obtained as solution of these runs are summarised in Table 6.

In the optimal solution obtained in the first computer run, it was observed that flow in some of the arcs were outside the prescribed ranges which were used to compute the unit costs for the model. This is an effect of the nonlinearity of the cost functions and as described before an iterative approach was used to correct errors due to linearization. New unit arc costs were computed based on optimal flows obtained in the 1st computer run and with these augmented costs, the second computer run was made. The optimal flow solution obtained in the arcs were now within the prescribed ranges and this solution was considered satisfactory. During the first and second runs, it was assumed that all hydel plants were available for power generation at their installed capacity during the peak demand period.

In the third computer run the available capacity during peak demand period was reduced to 75% of the installed capacity for all hydel plants. In addition to this locations at Rupar and RAPP were suppressed from further consideration for the location of the nuclear plant as during the first two runs these locations were not used. The result of reducing available hydel capacity is an increase in the utilisation of existing and proposed thermal plants and nuclear plants and an increase in total system cost as seen in Table 6.

In the fourth and fifth computer runs, the available hydel capacity was further reduced to 50% of the installed capacity. This might correspond to a dry year and indicated the additional thermal capacity that should be built in to counteract the adverse effects of a dry year. The nuclear plant locations at Narora and Matatila were compared in the fourth and fifth runs, the fourth run considered Matatila and the fifth run had Narora as the location. As Table 6 shows the Narora location ensures a higher utilisation of the nuclear plant with a corresponding reduction of system cost by Rs. 23 million.

The last run was made to increase the accuracy of the model solution and new unit transmission arc costs were computed for the arcs where power flow was outside the range originally used for computing the unit costs. The hydel plants at Kistwar and Pakal Dal were not utilised fully in earlier computer runs and hence these were dropped from consideration in the sixth run. The resulting generation schedule and utilisation of existing as well as proposed plants are shown in Table 6. Information regarding the available capacity of individual hydel plants were not available and further runs could be made to judiciously choose between hydel plants if such detailed information is obtained.

In all the solutions, the hydel plants are being utilised to the maximum possible extent except the proposed plants at Kistwar and Pakal Dal, as the cost of generation in hydel plants are the cheapest. Thus highest priority should be given to exploit the hydel resources and implement the proposed schemes. As the total installed hydel capacity may not be available during the peak demand period, specially following a dry year, proposed thermal plants at Faridabad, Panipat, Bhatinda, Kota and RAPP must be considered. Along with these plants the existing plants at Kanpur and Harduaganj would provide enough capacity if hydel capacity is not fully available. Proposed plants at Panki and Harduagang were found uneconomical with the cost data used, whereas the existing and proposed plants at Obra are utilised almost fully due to their better thermal efficiency and low cost of coal at Obra.

Narora seems to be the best candidate for the location of the nuclear plant as it has the highest utilization and this location results in a savings of Rs. 23 million in annual costs as compared to the location at Matatila, whereas locations at Rupar and RAPP are uneconomical.

Reserve requirements in the farm of spinning reserve or cold reserve to account for forced outages have not been explicitly considered in this model. This could be incorporate by increasing peak demand at each load centre by a fixed percentage and obtaining an additional computer run. The reserve capacity should be at least equal to the capacity of the largest unit in the system. However provision of reserve capacity is also intimately linked with system reliability and the design of the transmission network for which load flow studies are required.

In the optimal transmission network it was found that some of the proposed 400 KV lines were not fully utilised and there was not much interzonal power transfer.

However those lines may be necessary for the purpose of reliability and formation of the regional grid.

5. CONCLUSIONS

In this paper a Network Modelling Approach for the solution of the investment planning problem in electric power generation and transmission system is presented and illustrated with its application to the Northern Region of India. The network model scrutinizes the existing and proposed generating plants and transmission lines from the economic point of view so that power demands at the various load centres are satisfied at minimum annual cost to the system. The results of the study should be further examined by load flow studies for system reliability and other engineering considerations.

The study was made for the peak demand but could be followed for off-peak seasons. Such a series of studies would aid in the preparation of a maintenance schedule. The network model could be formulated for each year of the planning horizon if demand schedule is known. This would give some idea regarding the scheduling of commissioning of power plants and transmission lines during the planning horizon.

The network model assumes continuous ranges for power generation. As power plants are usually available in discrete sizes, if a plant in the optimal solution is not fully utilized, a plant of lower capacity could be suggested and the cost function correspondingly changed. Also a mixed integer programming approach would be useful to treat discrete sizes of power plants.

The network model solution is sensitive to the cost information used for generation and transmission and the selective choice of investment projects is made on the basis of cost differentials. It is thus essential that accurate cost estimates should be obtained and the range of errors in cost should be of the same order. Sensitivity analysis could be performed to study the effect of variations in capital or operating costs on project selection.

As better information on existing and proposed power systems becomes available, the network model could be further modified to improve its capability as a planning tool.

Even as it is formulated now it can provide valuable insight into the comparative economics of various alternative proposals for power generation and the adequacy of the existing and proposed transmission network for satisfying system demand.

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TABLE - I

Load Centres in Northern Region and Their Peak Demands in 1978 - 79

Sr. No.	Load Centre	Peak Demand (MW)	Sr. No.	Load Centre	Peak Demand (MW)
1.	Pipri	283	23.	Yamuna	37
2.	Mughalasari	293	24.	Jullundar	327
3.	Gorakhpur	261	25.	Ludhiana	411
4.	Sultanpur	183	26.	Muktasar	97
5.	Allahabad	149	27.	Sangrur	118
6.	Kanpur	423	28.	Bhatinda	148
7.	Lucknow	218	29.	Bhakra	381
8.	Mainpuri	149	30.	Rupar	56
9.	Bareilly	141	31.	Amritsar	276
10.	Harduaganj	189	32.	Udaipur	132
11.	Moradabad	162	33.	Kota	225
12.	Muradnagar	326	34.	RAPP	89
13.	Narora	63	35.	Jaipur	192
14.	Shamli	98	36.	Alwar	47
15.	Saharanpur	71	37.	Sawaimadhopur	61
16.	Delhi	660	38.	Jodhpur	29
17.	Ballabhgarh	252	39.	Khetri	46
18.	Nehtaur	56	40.	Ratnagarh	26
19.	Panipat	135	41.	Bikaner	23
20.	Hissar	214	42.	Beawar	40
21.	Rishikesh	101	43.	Bhilwara	40
22.	Roorkee	81			

TABLE - II

Existing and Proposed Generating Stations upto 1978-79 for Northern Region

Sr. No.	Generating Station	Type	Existing Proposed	Maximum capacity (MW)	Running Cost Rs./MWHr.	Capital Co Rs./MW insta
1.	Obra	Hydel	Existing	100	-	-
2.	Rihand	Hydel	Existing	300	-	1,537,000
3.	Obra	Thermal	Existing	1500	31.0	1,648,000
4.	Kanpur	Thermal	Existing	155	65.1	-
5.	Panki	Thermal	Proposed	220	71.2	3,520,000
6.	Harduaganj	Thermal	Existing	190	53.9	1,466,000
7.	Harduaganj (Extn.)	Thermal	Proposed	550	53.9	2,000,000
8.	Tehri	Hydel	Proposed	300	-	2,170,000
9.	Ramganga	Hydel	Existing	240	-	1,849,000
10.	Delhi	Thermal	Existing	360	41.7	1,890,000
11.	Faridabad	Thermal	Proposed	400	39.8	1,641,700
12.	Panipat	Thermal	Proposed	220	39.1	1,980,000
13.	Yamuna (Stages I to IV)	Hydel	Existing	800	-	2,170,000
14.	Maneri Bhali	Hydel	Proposed	405	-	3,474,000
15.	Vishnu Prag	Hydel	Proposed	120	-	1,414,000
16.	Bhakra L.B.	Hydel	Existing	450	-	1,317,000
17.	Bhakra R.B.	Hydel	Existing	600	-	1,317,000
18.	Dehar	Hydel	Existing	340	-	2,730,000
19.	Dehar (Extn.)	Hydel	Existing	660	-	1,594,000
20.	Siul	Hydel	Existing	200	-	1,024,000
21.	Thein	Hydel	Proposed	420	-	-
22.	Seawa	Hydel	Proposed	100	-	1,024,000
23.	Salal	Hydel	Existing	270	-	2,043,000
24.	Kistwar	Hydel	Proposed	200	-	2,043,000
25.	Pakal dal	Hydel	Proposed	200	-	2,043,000
26.	Bhatinda	Thermal	Existing	220	42.2	1,980,000
27.	Bhatinda (Extn.)	Thermal	Proposed	220	42.2	1,881,000
28.	RP Sagar	Thermal	Existing	172	39.4	-
29.	Kota	Thermal	Proposed	440	40.7	1,503,000
30.	RAPP	Thermal	Proposed	400	40.7	1,503,000
31.	Rupar*	Nuclear	Proposed	470	10.43	3,451,000
32.	Narora*	Nuclear	Proposed	470	10.45	3,451,000
33.	Matatila*	Nuclear	Proposed	470	10.45	3,451,000
34.	RAPP*	Nuclear	Proposed	470	10.45	3,451,000

*These are 4 alternative locations for the proposed Nuclear plant.

Table 3

Existing and Proposed Transmission Lines up to 1978 - 1979

S No	Transmission Lines	Existing/ Proposed	Rating KV	Route length KM
1	2	3	4	5
1.	Obra - Pipri	Existing	132 DC	34
2.	Obra - Pripri	Proposed	220 DC	34
3.	Pipri - Mughalsarai	E	132 DC	129
4.	Mughalsarai - Gorakhpur	E	132 DC	204
5.	Mughalsarai - Gorakhpur	P	220 DC	204
6.	Obra - Mughalsarai	E	220 DC	97
7.	Obra - Mughalsarai	P	400 SC	97
8.	Obra - Sultanpur	E	400 SC	253
9.	Sultanpur - Gorakhpur	E	220 SC	148
10.	Obra - Allahabad	E	220 DC	177
11.	Obra - Allahabad	P	400 SC	177
12.	Allahabad - Sultanpur	E	132 SC	111
13.	Allahabad - Kanpur	E	220 DC	208
14.	Kanpur (Gen.) - Kanpur	E	220 DC	0
15.	Kanpur - Lucknow	E	220 DC	90
16.	Kanpur - Lucknow	E	132 SC	90
17.	Kanpur - Lucknow	P	220 SC	90
18.	Sultanpur - Lucknow	P	220 SC	130
19.	Kanpur - Mainpuri	E	220	150
20.	Matatila - Kanpur	E	132 SC	257
21.	Matatila - Kanpur	P	220 SC	257
22.	Matatila - Allahabad	P	220 SC	230
23.	Matatila - RAPP	P	220 SC	230
24.	Lucknow - Bareilly	E	132 DC	259
25.	Tehri - Bareilly	P	220 DC	200
26.	Mainpuri - Harduaganj	E	220 DC	128
27.	Harduaganj (Gen.) - Harduaganj	P	220 DC	0
28.	Harduaganj - Muradnagar	P	220 DC	105
29.	Harduaganj - Muradnagar	P	400 SC	105
30.	Narora - Harduaganj	P	220 SC	65
31.	Narora - Muradabad	P	220 SC	65
32.	Narora - Mainpuri	P	220 SC	135
33.	Moradabad - Bareilly	E	132 DC	85
34.	Muradnagar - Muradabad	E	132 SC	128
35.	Rishikesh (Gen) - Rishikesh	P	220 DC	0
36.	Rishikesh - Muradnagar	P	400 SC	175

Table:3(contd.)

Sl No.	Transmission Line	Existing/ Proposed	Rating KV	Route Length KM
37.	Rishikesh - Muradabad	P	400 SC	160
38.	Moradabad - Nehtaur	E	132 DC	64
39.	Nehtaur - Roorkhee	E	132 DC	83
40.	Rishikesh - Muradnagar	E	220 SC	175
41.	Rishikesh - Roorkhee	E	132 SC	49
42.	Saharanpur - Roorkhee	E	132 SC	31
43.	Muradnagar - Shamli	E	220 SC	48
44.	Shamli - Sahranpur	E	220 SC	50
45.	Yamuna - Saharanpur	E	220 SC	85
46.	Yamuna - Rishikesh	E	220 SC	70
47.	Shamli - Panipat	E	220 SC	160
48.	Muradnagar - Delhi	E	220 DC	43
49.	Hissar - Panipat	E	132 SC	115
50.	Hissar - Delhi	E	220 DC	198
51.	Hisser - Battabhgarh	P	220 DC	225
52.	Bhakra - Panipat	E	400 SC	280
53.	Bhakra - Panipat	P	400 SC	280
54.	Bhakra - Rupar	E	132 DC	70
55.	Rupar- Ludhiana	E	132 DC	100
56.	Rupar - Sangrur	P	220 DC	135
57.	Bhakra - Ludhiana	E	220 DC	86
58.	Bhakra - Ludhiana	E	220 DC	86
59.	Ludhiana - Jullundar	E	220 DC	58
60.	Ludhiana - Jullundar	E	132 SC	58
61.	Ludhiana - Jullundar	E	220 SC	58
62.	Dasuya - Jullundar	E	220 DC	56
63.	Dasuya - Jullundar	P	220 SC	56
64.	Jullundar - Amritsar	E	220 SC	80
65.	Jullundar - Amritsar	E	132 SC	80
66.	Ludhiana - Bhatinda	E	220 SC	128
67.	Bhatinda - Sangrur	E	220 SC	112
68.	Ludhiana - Muktasar	E	132 DC	144
69.	Ludhiana - Sangrur	E	220 DC	240
70.	Sangrur - Hissar	E	220 DC	144
71.	Hissar - Khetri	E	220 SC	115
72.	Jaipur - Khetri	E	220 SC	144
73.	Hissar - Ratangarh	E	132 SC	208
74.	Panipat - Jaipur	E	220 SC	280
75.	Panipat - Jaipur	P	400 SC	280
76.	Alwar - Delhi	E	220 SC	125
77.	Jaipur - Alwar	E	220 SC	100
78.	Jaipur - Alwar	E	132 SC	100
79.	Alwar - Harduaganj	E	132 SC	210

SC - Single circuit
DC - Double circuit

Sl No.	Trans
80.	Mainp
81.	Sawai
82.	Sawai
83.	Jaipu
84.	Jaipu
85.	Beawe
86.	Bhilw
87.	Bhilw
88.	RAPP
89.	Kota
90.	Kota
91.	Kota
92.	RAPP
93.	Kota
94.	Kota
95.	Kota
96.	Morad
97.	Yamun
98.	Sahar
99.	Yamun
100.	Hissa

Table 3 (contd.)

Sl No.	Transmission Lines	Existing/ Proposed	Rating KV	Route Length KM
80.	Mainpuri - Sawaimadhopur	E	132 SC	325
81.	Sawaimadhopur - Jaipur	E	132 SC	128
82.	Sawaimadhopur - Jaipur	P	220 SC	128
83.	Jaipur - Beawar	E	132 SC	200
84.	Jaipur - Beawar	P	220 SC	200
85.	Beawar - Jodhpur	E	132 SC	152
86.	Bhilwara - Jodhpur	E	132 SC	245
87.	Bhilwara - Beawar	E	132 SC	93
88.	RAPP - Bhilwara	E	132 SC	120
89.	Kota - Bilwara	E	132 SC	120
90.	Kota - RAPP	E	220 DC	43
91.	Kota - Jaipur	E	220 DC	187
92.	RAPP - Jaipur	P	400 SC	230
93.	Kota - Beawar	P	220 SC	187
94.	Kota - Sawaimadhopure	E	132 DC	112
95.	Kota - Sawaimadhopur	P	220 SC	112
96.	Moradabad - Nehtaur	P	220 DC	64
97.	Yamuna Saharanpur	P	220 SC	85
98.	Saharanpur - Roorkee	P	132 SC	31
99.	Yamuna - Muradnagar	P	400 SC	260
100.	Hissar - Panipat	P	220 SC	115

E	Existing
P	Proposed

TABLE - IV

Characteristics for Various Transmission Lines

Sr. No.	Transmission Line KV Rating	Conductor Size, mm^2	K Factor Watts.	Capital Cost Rs. lakhs/Km	Range of Power Transmission M
1.	400 KV SC	325	0.505	2.75	150 - 600
2.	220 KV DC	325	0.835	2.30	100 - 300
3.	220 KV SC	325	1.669	1.37	50 - 150
4.	132 KV DC	185	4.065	1.27	50 - 100
5.	132 KV SC	185	8.13	0.78	0 - 50

SC - Single Circuit

DC - Double Circuit

TABLE - V

Cost of Transmission Used for the Study

(Values are taken from the graphs plotted)

Existing Lines	Cost, Rs./KM/Year/MW	Range, MW
132 KV SC	140	40 - 50
132 KV DC	140	80 - 100
220 KV SC	85	120 - 150
220 KV DC	85	240 - 300
400 KV SC	110	500 - 600

Proposed Lines	Cost, Rs./KM/Year/MW	Range, MW
132 KV SC	370	40 - 50
132 KV DC	335	80 - 100
220 KV SC	200	120 - 150
220 KV DC	185	200 - 300
400 KV SC	150	400 - 600

Range of Power Transmission M
150 - 600
100 - 300
50 - 150
50 - 100
0 - 50

Table 6

Pattern of Plant Utilisation Under Different Assumptions: Summary of Computer Runs

Type	Generating Stations	Max Capacity MW	Power generated in MW in the optimal solution					
			1st run	2nd run	3rd run	4th run	5th run	6th
Existing Hydel Plants.	Rihand Obra	(400)	400	400	300	200	200	200
	Ramganga	(240)	240	240	200	120	120	120
	Yamuna	(800)	650	650	400	400	400	400
	(Bhakra L.B., R.B., Dehar I & II)	(2050)	2050	2050	1600	1025	1025	1025
	Siul	(200)	200	200	160	100	100	100
	Salal	(270)	270	270	220	130	130	130
Existing Thermal Plants	Obra	(1500)	1219	1219	1319	1419	1419	1419
	Kanpur	(155)	-	-	-	155	155	143
	Harduaganj	(190)	-	-	162	190	190	190
	Delhi	(360)	360	360	360	360	360	360
	Bhatinda	(220)	72	116	220	220	220	220
	RP Sagar	(172)	172	172	172	172	172	172
	Tehri	(300)	300	300	250	150	150	150
Proposed Thermal plants	Panki	(220)	-	-	-	-	-	-
	Harduaganj	(550)	-	-	-	-	-	-
	Faridabad	(400)	-	-	-	-	400	400
	Panipat	(220)	-	-	-	220	220	220
	Bhatinda	(220)	-	-	-	103	90	128
	Kota & RAPP	(840)	-	-	275	840	840	840
Proposed Hydel Plants	Tehri	(300)	300	300	250	150	150	150
	Rishikesh (Maneri bhali & Vishnu Prag)	(525)	525	525	420	260	260	260
	Dasuya (Thein & Seawa)	(520)	520	520	420	260	260	260
	Amritsar (Kistwar & Pakal dal)	(400)	113	-	157	26	26	-

(contd.).

Table 6 contd.

Type	Generating Stations with maximum capacity in MW	Power generated in MW					
		1st run	2nd run	3rd run	4th run	5th run	6th run
Proposed Locations for a nuclear plant	Rupar(470)	-	-	-	-	-	-
	Narora (470)	-	20	212	-	363	363
	Matatila (470)	123	178	273	350	-	-
	RAPP (470)	6	-	-	-	-	-
Total cost in Rs. million per annum.		1471	1488	1858	2576	2553	2557

Notes: In 3rd run Hydel capacity was reduced to 75% of maximum and Rupar, RAPP locations were neglected for proposed nuclear plant.

In 4th run Hydel capacity was reduced to 50% of maximum and nuclear plant location at Matatila was considered.

In 5th run Hydel capacity was reduced to 50% of maximum and nuclear plant location at Narora was considered.

In 6th run proposed hydel plants at Kistwar & Pakal dal were neglected and costs on some transmission lines were changed for increasing accuracy.

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