OPTIMAL OPERATION OF POWER SYSTEM WITH MULTI RESERVOIRS AS APPLIED TO BHAKRA-BEAS SYSTEM

A THESIS

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WATER RESOURCES DEVELOPMENT

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled,' OPTIMAL OPERATION OF .. POWER SYSTEM WITH MULTIRESERVOIRS AS APPLIED TO BHAKRA-BEAS SYSTEM' in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy, submitted in the Department of Water Resources Development Training Centre of the University is an authentic record of my own work carried out during the period from June, 1978 to August 1983 under the supervision of Prof. O.D. Thapar and Dr. G.N. Yoganarasimhan.

The matter embodied in this thesis has not been submitted by me for the award of any other degree.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Expanding Multi Reservoir Systems are being created to meet increasing demand of water and power. Operation practices and decisions based on judgemental decisions still being followed cannot be optimal. These decisions are also unable to take into account the requirements of interconnections and integrated operations. Optimization techniques are necessary to manage operations of such complex systems. These techniques have been applied to analyse and to improve existing system operations of Bhakra-Beas multireservoir system. Some of the solutions have been accepted by Bhakra-Beas Management Board. Three case oriented studies have been carried out by modelling of the system by development of algorithms, solution techniques and analysis of results for monthly, daily and hourly operations.

Multireservoir medium range study with two objectives for minimizing the deviations from irrigation targets and maximization of power generation for these systems has been done. Multireservoir decomposition approach is used for converting the problem into sub problems which are solved by generalised reduced gradient and conjugate gradient techniques. The analysis has resulted into increase in annual average power generation, meeting the scheduled irrigation targets and bringing the reservoirs to their full supply level in the end of the study period. It has been suggested that instead of spilling from Pong reservoir water should be drawn from Bhakra reservoir effecting additional power generation.

A new method for unit commitment and scheduling generation in two Bhakra power plants below a common dam is developed. This results into optimum releases through each turbine and number of turbines to be operated for meeting demand at a particular reservoir level. A variety of plant operating constraints has been considered. Discharge minimization has been taken as the objective function solved by non linear and integer programming techniques. Obtained results indicate 0.5 to 2 percent saving in water. Developed unit commitment and generation schedules are being followed by plant operators.

Hourly optimization model has been developed for off-line applications for the operation of balancing reservoir and power plant, of newly constructed Beas Satluj Link Project. The objective has been to find hourly release schedules, maximize hourly power generation and meeting system peaks. This would further maximize energy generation in the day and transfer maximum water to Bhakra reservoir for increasing energy generation at Bhakra Power Plants. Compared results with so far field operations are encouraging and still improving the operations.

The developed optimization models could permit easy generalization and possible application at other facilities.

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i	Machine index
I_n	Inflows
IDPSA	Incremental Dynamic Approximation
K	Iteration index
Kharif	Monsoon season, June-Octob
MW	Mega watt
N	Number of Machines
Nr	Number of Reservoirs
NLP	Non Linear Programming
O	Outflow
PG	Machine generation
$\overline{PG}$	Upper generation limit
$\underline{PG}$	Lower generation limit
PD	System load including auxiliary power supply requirement
PGTL	Total generation of all the generators scheduled for operation
PPG	Power Plant Generation
PRS	Pandoh Reservoir storage at Pandoh
PL	System Load
PS	System spinning reserve requirement
PRL	Pandoh Reservoir level
PT	Interlinking Transformer Capacity at Bhakra
P^{NF}	Nangal Fertilizer Factory Load
Q	Discharge
QL	Minimum discharge for Tail Water Level
QTL	Total discharge from all running turbines
QB	Discharge from Balancing Reservoir for Power generation in Plant through Sundernagar Slapper tunnel

Xi	Binary variable i.e. 0,1
Xn	Minimum reservoir storage
Xm	Maximum reservoir storage
Z	Objective function
α	Load step
λ	Lagrangian
ϵ	Tolerance
δ	Step size
TWLI BRLI EFHI PRLI BRSVI	Initial values
TWLF BRLF EFHF PRLF BRSVF	Final values
BRSLU TWLU PGU	Upper limits
BRSLL TWLL PGL	Lower limits

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CHAPTER 1

STUDY OBJECTIVE AND LITERATURE REVIEW

1.1 Introduction

The efficient use and management of multipurpose water resource systems is crucial in the era of water and energy shortage. There is ever-increasing demand for its judicious use. Operations of water resource projects tend to become complex by subsequent upper valley and interbasin developments. It is rare that a complete water resource system is designed at the same time from the start to finish. The operation planning of such a complex system consisting of water grid and electric grid is a difficult problem. Water grid planning is concerned with the fundamental problem of modifying the time and space availability of water for various purposes in order to accomplish certain basic regional and local objectives. It needs historical record of stream inflows, reservoir system, water demands and social commitments. Electrical grid operation consists of availability of power plants, unit commitment, generation scheduling (economic operation) and load forecasting etc.

Generating capacity in a power system can be increased by development of new sites, by the addition of generating facilities at existing water resource projects and from planned operation of existing hydropower systems. This operation may or may not conflict with the existing practices. It includes new or variable operating rules, reallocation of storage and other operating practices for the multireservoir system that could increase average storage capacity or energy capability, assessment of varying irrigation and power requirements and distribution of available water and energy in actual need based proportions. Maximum energy capability computation of the hydrosystem is a deterministic, discrete-time problem concerned with management of reservoir storage which may be daily, weekly or seasonal. A large power system invariably includes a variety of generating plants. Hence, optimal generation scheduling is the on line process of allocating the total generation among the various power plants and units for energy maximization and peak shaving. It is important from reliability considerations.

Over the past decades, increasing attention has been given to the use of mathematical (simulation and optimization) models for deriving operating policies of multireservoir systems. In some cases, with only small improvements in system operation even 1 or 2 percent increase in hydropower production, a substantial increase in annual economic benefits can be realized. This appreciation has been coupled with a substantial research effort through the years, and has led to continuing developments in the conceptual thinking and the mathematical formulations for a variety of models.

It is in this context necessary for reassessing the existing system operation practices by systems approach techniques for optimizing the operation of multipurpose multireservoir system. Critical examination of Bhakra-Beas system has been made with the evolved techniques.

1.2 Methodology

In water reservoir systems planning and management problems extensive use of mathematical modelling techniques as parts of system analysis methodologies have been carried out in the past. These investigations do not point toward any axiomatic approach, particularly due to the fact that the techniques to be employed are dependent on availability of data, objectives, performance requirements and the uncertainties involved in a decision making process. This study is confined to multipurpose, multireservoir Bhakra-Beas System, a part of Indus Water system. Discussions with the managing engineers led to examine the operating procedures, test and compare alternative strategies for improving system operation. On carrying out studies of Bhakra-Beas reservoir system, large amount of factual data for the analysis was collected and some was taken from the published literature with regard to (a) rivers' inflows (b) outflows (c) reservoirs' data (d) inter river water transfers (e) irrigation targets (f) power plants and machines data (g) load curves indicating peak and energy targets (h) operating practices of different sub-systems

(i) operating limitations (j) details of other components-tunnels, canals, diversion structures, channels etc. of each project.

As a basis for conducting the study a framework was developed within which various operational objectives could be individually studied. The methodology followed is as under :

a) modelling of the system,

b) development of solution techniques and algorithms,

c) establishing validity of optimization programmes by trial runs and carrying out studies to Bhakra-Beas reservoir system, and

d) analysis of results and discussions and recommendations.

The time steps considered in the models are also significant factors in making specific assumption and choosing proper techniques. The medium term planning models are generally seasonal in character and can effectively use historical information, real time or short term models should be capable of incorporating real time, short term information. Both short range and seasonal operation models have been applied for the analysis of field problems.

1.3 Study Objectives

The objectives of operation are of prime importance in developing an operation policy, whether these are stated explicitly in the objective function or incorporated implicitly as binding constraints in the model. The literature is dominated by work involving optimization of operation where the volume of water released from the reservoir has been principle issue. But different conclusions result when multiple objectivesare to be satisfied. The consideration of a second objective may be in the constraints such as actual storage state, meeting a particular load curve and reserve and forecasts of future streamflow are important issues that influence mathematically derived reservoir operation policies.

There is a variety of operating policies in use. Some of them define each reservoir's target level without any information on what to do if levels fall below the minimum limits. Other operating policies define precisely how much water to withdraw at different control structures. The objective of this study is to use optimization techniques for the analysis and improvement of the operation and management of Bhakra-Beas system. Medium range and short range studies have been carried out with the following objectives :

i) to study past operation of Bhakra-Beas reservoir system;

ii) medium range optimization study for optimal power generation at Bhakra-Beas reservoirs system with minimization of probable deviations from release targets and to reconsider operational strategies,

iii) to minimize power discharges from Bhakra dam power stations and consequently increasing energy generation by short range unit commitment and generation scheduling optimization study and to consider online operation possibility, and

iv) to formulate the optimal daily schedules of regulation for newly constructed Beas Satluj Link Balancing Pond of Dehar hydroelectric power plant for optimum peaking and energy and maximum water transfer from Beas river to Satluj river to achieve increase in capacity at Bhakra.

1.4 Literature Review

Over the past several years a number of researchers, field engineers and managers have produced vast literature on this subject. Initially, the aim was to develop rule curve for guiding the releases from a single storage reservoir. Good work started around 1955 with systems analysis application. This helped in the management of river basins and power systems analysis which are complex and dynamic in nature for their planning, operation control and operation planning. Research work had included the analysis of simple reservoir system with single and multiobjectives, multireservoirs with multiobjectives, inflow forecasting, hydrological studies etc. In the power system operation work had been done for the stability, optimal operation- optimum economic generation, peak shaving, load forecasting, energy maximization, secure and reliable operation, economic dispatch, generation scheduling unit commitment, maintenance scheduling, generation control etc.

Only a few had reported the management of multireservoirs with optimal operation of power system. It is felt to review the literature only connected to this work in the field of multireservoir and optimal power system operation in this section and in other chapters where found necessary. Other literature which was also referred to this work has been given in the references.

1.4.1. Multireservoir Operation

1.4.1.1 Yearly operation

J.D.C. Little (74) considered sequential decision problem with variable head and stochastic flows. He used stochastic dynamic programming with two state variables to determine the monthly optimal operation. His set cost function manipulation to show that the only additional information needed for finding the optimum decision function in one interval is an expected cost function for the succeeding interval. The minimum expected cost corresponds to the maximum expected hydroelectric energy.

In this paper (35) considered several methods of treating the effect of head variations upon the hydroplant characteristics in determining the optimum mode of operation. Head variation could be accounted by multiplying the incremental water rate by a water conversion coefficient which remained constant over the time period, non-linear differential equations were solved by numerical integration.

F.L. Chernous'ko presented (16) a local variation method for the numerical solution of variational problems and finds the local minima of functions. As claimed by the author compared to dynamic programming technique, it enabled the number of operations and the amount of information stored during the solution to be reduced and applicable to linear and nonlinear boundary problems which reduce to variational problems.

Solution of problems of optimal control by the method of local variations had been given by Krylov et al.(67). The application of the technique was studied in detail (85) considering a system of reservoirs with some variations in the method. It had been observed that since the final value was sensitive to trial trajectories, the best value of trajectory should be chosen to start with. The number of operations were less and less information was to be stored during the solution hence total processing time was considerably less compared to other technique used. However, the technique has a characteristic that it leads to a local optimum and can be useful if initial trajectory is obtained by some other method.

W.A. Hall et al.(40) made the optimization study for a multipurpose reservoir system quite characteristics of all reservoirs whose principal purposes were the production of hydroelectric power and water conservation. Dynamic programming was used by considering the physical and hydrological

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S.I.D.P. and successive approximation. Four problems solved, range from hourly control of a system involving hydroelectric power, water storage and irrigation to long range optimum investment planning.

J. Sharma and T.S.M. Rao (101) formulated three interconnected reservoir system stochastic problem, used chance constrained programming technique for converting the problem into deterministic one and solved by a feasible decomposition method for finding optimal operating policy.

Monte Carlo approach to optimization of the operation rules for a system of storage reservoirs was applied by Jamusz Kindler (63). The implicit stochastic optimization by combining streamflow synthesis, simulation within which the optimization algorithm is nested and regression analysis seems to be a valuable technique.

O.T. Sigvaldason (103) described a simulation procedure being used for late winter-spring operation for the Rideau and Cataraqui multireservoir systems in Canada. It consisted of forecasts of cumulative runoff and formulized decision procedures at half monthly intervals and applied for both wet and dry historical years.

1.4.1.2 Weekly/Daily operation

C.R. Gagnon and J.F. Bolton (33) formulated the hydro scheduling problem of power plants on columbia river main stern and Lower Snake river as an unconstrained nonlinear optimization using penalty functions for the constraints and method of conjugate gradients for optimization. The deterministic approach faced departures from forecasted quantities but were accounted for by repeated analysis. The time horizon of one week with 8-hour-increments was considered. Fixed water-to-energy conversion factors were used to calculate energy generated. The result would be approximate only. Energy savings claimed were 0.2 percent of the total weekly average load.

The work in the area of real time operation is new and was started in the recent past. Jamieson and Wilkinson (57) developed an automated control strategy for flood control. Dynamic programming was used. Fults and Hancock (30) applied incremental dynamic programming for evaluating the daily water and power operating strategy. But its use was limited to a small system because of dimensional problems.

Becker and Yeh (6) developed a methodology for real time water and power optimization which utilises a form of dynamic programming for the selection of an optimal reservoir storage policy path through a specified number of policy periods while an iterative linear programming was used for period by period optimization. No initial policy was needed with no particular restriction for ensuring convergence.

Becker and Yeh (5) conducted large scale multireservoirs system optimization of real-time daily operation. Daily model of Central Valley Project (CVP) in California was developed for optimizing hydroelectric energy production ending storage vector relationship by minimizing the loss of potential energy of the stored water in reservoirs resulting from any release policy. Linear programming was used. As claimed it is compatible with present CVP monthly optimization procedures and the outputs could be utilised as inputs to an hourly programme. An improvement in generated megawatt hours of several percent over that generated using the present daily scheduling routine was anticipated.

Large scale maximization of energy capability for Pacific Northwest Hydroelectric system was done as a nonlinear programming problem, (49,32). The method of conjugate gradient was applied. The problem was converted into unconstrained reservoir system by regarding the bulk of constraints as soft and transferring them to the objective function by means of penalty terms. A good initial trajectory was required.

An approach towards the systematic posterior study of short-run (weekly, daily) operating practices for a reservoir system was developed and illustrated for an existing system of four large reservoirs (34). Simulation had been considered as superior technique for these problems, whereas optimization was considered screening device. A combined use of optimization and simulation models was indicated.

Optimal weekly releases from seasonal reservoirs were studied for the production of electrical energy (73) and first developed for the deterministic case. It was based on the solutions of the system of equations given by Kun-Tucker conditions.

1.4.1.3 Real time hourly operations

The integrated operation of water reservoir and power projects requires advance scheduling of hydroelectric energy generation on shorter periods. Real-time operation implies the optimal operation of an existing reservoir system and decisions regarding releases for various purposes have to be made on a short time period. This is a new area with large research scope. Only a few research publications have been produced. Optimization and simulation both techniques are under use.

First, Hourly Power Pondage studies for a practical system (Columbia River and Tributaries) was conducted in(19). These planning studies were preliminary for the evaluation of system operation impacts for 1980 conditions. Their purpose was explorating rather than definitive and did not reflect the imperfections of real life system operation. Simulation technique was used for determining the water surface and discharge fluctuation, load variations, automation of plant loading by load frequency break point method.

Hydro-Thermal power system hourly load distribution and pondage analysis was done for North West power pool(98). The programme simulate the hour by hour operation of each plant in the system for a seven day period. Electrical load gets distributed amongst conventional hydro, pumped storage and thermal plants. For each hour's operation the objective was to compute for each project, the project release, power generation, head and water surface elevations for forebay and tailwater. Hydrographs and duration curves of releases and water surface elevations at selected points could be plotted. Hydro system peaking capability and energy generated was calculated.

In real time operation the unexpected equipment to breakdown, streamflow and power load forecasts' deviations, was often the rule rather than the exception and simulation must include this contingency. The programme was used to study the effects of hourly coordination on energy exchanges between the various power systems.

The critical period optimizer programme was developed (113) to compute optimum critical period hydro regulation. As claimed it operates iteratively by computing successively improved approximations to the solution starting with initial approximation. Weight factors were used in the programme to keep the operational violations under tolerance.

The hourly model was developed for on line use in the operation, in the report (116,17) for Central Valley Project in California. It was a part of the overall decision model and designed to be used in conjunction with monthly and daily programmes. The developed procedure in two phases involves determination of a good feasible policy through an iterated linear programming and adjust process. For second phase this acts as a starting policy for an incremental dynamic programming successive approximations process to derive an optimal policy. It had resulted into more efficient hydro power production and schedule of generation and optimal releases policy.

Non-linear programming algorithm for real-time hourly operation for single reservoir system had been studied by Armando Balloffet et al.(3) with the objective of maximizing hourly generation to meet power schedules, daily flow requirement for water supply etc. To solve the nonlinear concave objective function with nonlinear concave and linear constraints, nonlinear duality theorems and Lagrangian procedures were applied. Lagrangian was carried out by a modified gradient projection technique alongwith a stepsize determination routine, as convergence of the algorithms found to be too slow. This study could be extended to multireservoirs by making use of Dantzig-Wolfe Decomposition and Lagrangian procedures.

A.Diacon et al. (23) presented a general model of Romanian hydrosystems with probability density functions of sentative and indicative of a single unit. Thus knowing the optimum way of operating K units, K+1 units optimum way could be found out.

The work presented by H.H. Happ et al.(44) reported up on the development of a unit commitment method and its implementation in program form a large scale hydrothermal system. The method satisfied many operating and other constraints and claimed to be useful for actual operations and operation planning. The approach consisted of two blocks called suboptimizer and optimizer. The former obtained a feasible schedule close to the optimal and later optimized the schedule. The savings realizable over manual methods were reported to be in excess of one percent of the total fuel cost. The evaluation of the effect on economy and security of the system by changing the operating rules, reserve requirements, unit additions, and outages, unit limitations and interchanges could be determined.

A reliability oriented unit commitment study was done by A.V. Jain and R. Billinton (56) involving two basic elements, economic scheduling of the operating units over the commitment period and the application of the reliability techniques to these hourly schedules. A primary attempt to apply reliability techniques was also made by J.D. Guy(38) and A.K. Ayoub and A.D. Paton (2) for thermal systems only.

Unit commitment in hydro-thermal system was performed in general by first fixing the hydro generation. The reliability method included the outline generating unit derated states. All the capacity available was represented in the form of a single large generating unit with a large number of derated states. This equivalent multilayered unit was backed up by all the standby resources. A standard risk level had been used to operate the system with a consistent reliability at every hour for the next scheduled period. It could also be used to determine incremental reliability costs associated with the selection of a particular level of operating capacity reliability.

A recent short paper reported by A. Turgeon (110) described a new and rigorous method for determining the mode of operation of an electrical system that minimizes the operational cost. The study was not reported with intention of applying immediately to practical system, rather than to find an exact and computationally feasible solution to the basic scheduling problem. The method used the maximum principle of Pontryagin to determine the generation levels of the operating units, to devise additional criterion for fathoming a vertex in the branch and bound algorithm and to reduce the number of units considered for shut down. The choice of which units to shut down from those suggested by the maximum principle was done by branch and bound.

1.5 Organisation of the Study

The study is reported in the following sequence :

a) Multireservoir generation system operation models, analysis and optimization are briefly reviewed in Chapter-II.

b) Medium range optimization study for Bhakra-Beas multireservoir system has been reported in Chapter-III and IV.

c) Unit commitment and generation scheduling problem of two power plants below Bhakra dam of Bhakra-Beas System analysed with integer programming and nonlinear programming techniques are described in Chapter-V.

d) Daily Pond Optimization study pertaining to newly constructed power plant is mentioned in Chapter-VI.

e) Conclusions, recommendations and scope for future work are presented in Chapter-VII.

CHAPTER II

MULTIRESERVOIR OPERATION MODELS

2.1 Introduction

A water resource development project catering to water supply, irrigation or hydroelectric power generation, directly from a stream, may be unable to meet the pattern of demand during extremely low flows. Storage reservoirs can retain excess water from periods of high inflow for use during period of low inflow. Flood water storage also reduces damages downstream. The releases of stored water may be for a variety of uses - power production, irrigation, industrial and public water supply, maintenance of navigation depths, fish and wild life preservation, cooling water for thermal power stations and other industries, prevention of salt intrusion and dilution for sanitary purposes, pollution control etc. The main function of a reservoir system is stabilization of flow by regulation. Water grid demands are to be expressed as minimum desired and minimum required flows to be met at selected locations. The specification of operating rules of a reservoir include the storage volume allocation with time, priority of meeting demands at various locations. These rules should govern diversion schedules, maintain minimum flows and balance storage amongst reservoirs. Operation policies have to be designed to vary seasonally in response to the seasonal demands for water and the stochastic nature of supplies.

On the power grid side rapid increase in energy demand is there in the developing areas and the demand is doubling every 5-7 years. Hence, the importance of optimum economic operation of hydroelectric project has increased greatly. A little saving in the production cost per unit would integrate to a considerable amount. The basic objective of optimal operation is to match system generation with the load in the most economical manner keeping the power flows, bus voltages, active and reactive powers and system frequency within limits.

Application of optimum generation, system operation and control consisting of optimal generation scheduling and load frequency control is the only answer for managing larger and complex interconnected power and water grids and necessitate the analysis of power system with multireservoirs.

2.2 Conflicts on Reservoir Operations

Conflicts that arise from multi-purpose use of water are (a) conflict in space (b) conflict in time (c) conflict in discharge. Consider flood control in conflict with various conservation purposes. These purposes require filling of reservoirs during atleast some period. Some of the conservation uses are power generation, water supply and recreation etc. However, flood control is enhanced to the degree that a reservoir is emptied. The more empty a reservoir the greater is the probability of a future flood being contained by the reservoir. Fig.2.1 explains the conflicting operating rules.

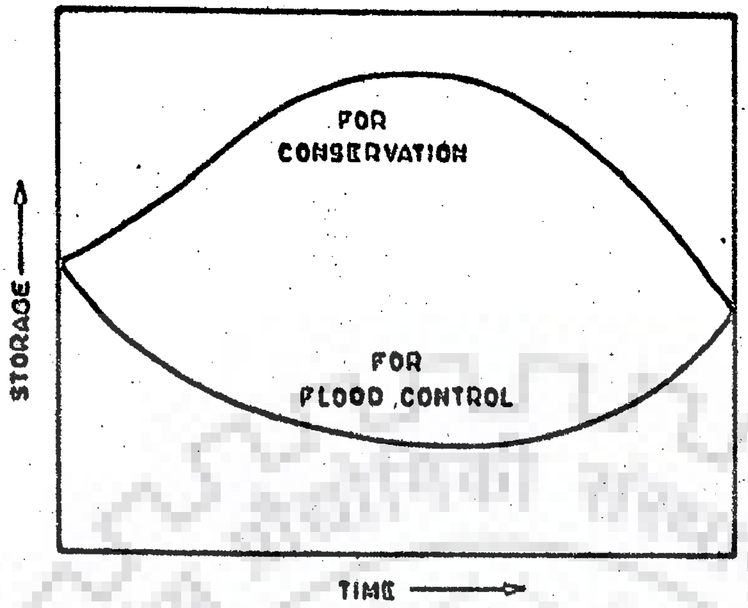


FIG. 2·1 CONFLICTING OPERATING RULE

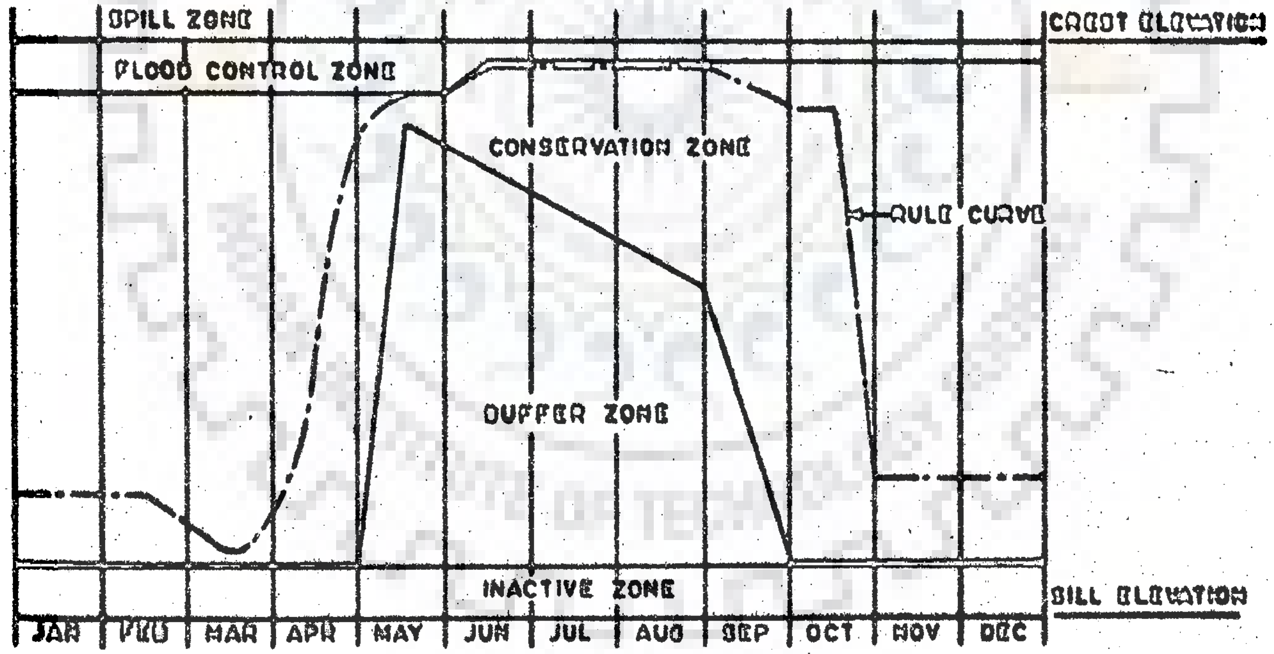


FIG. 2·2 (a) ZONES AND RULE CURVE FOR A TYPICAL RESERVOIR

2.3 Rules and Regulations for Reservoir Operation

The plan for regulating the outflow from a reservoir and consequently its content is defined as the Operating Rule. The specification of operating rules at a reservoir side include the volume of storage allocated to the pool by time period, identification of each downstream location for which the reservoir has to operate and the priority system upon which the reservoir meets the demand. These rules may govern diversion schedules, maintain minimum flows and balance storage among reservoirs based upon the current state of the system.

A reservoir regulation plan initially collects and synthesises all design study material for the reservoirs under consideration. The regulation plan's objective is to guide the operation of reservoir so as to pursue as best as possible the stated design objectives. As such these plans carry legal weight and their modification is institutionally constrained. A schedule of regulation is a one or two page summary of a regulation plan's recommendations. It lists (a) a rule curve (b) a number of schedules (c) various pool elevations, outflow and river stage constraints. The rule curve is a pool elevation-time diagram. It specifies the recommended and therefore, intended use of storage. It represents the strategy or long run operating policy and reflects principal objectives. During the floods and droughts a reservoir's level will inevitably deviate from rule curve levels. A schedule of regulation also specifies the procedures for returning the pool to rule curve levels.

Schedules of regulation are to be considered as guides to reservoir regulators. Their long-run policy element- the rule curve may be modified as a result of new data, additional experience or changing objectives. For finding rule curves among the various reservoirs in the system the critical conditions should not be attained simultaneously. In case of two reservoirs in series the upstream reservoir release schedule will bias the development of rule curve of downstream. For parallel reservoirs the best rule curve will require apportionment of releases from two or more reservoirs based upon available storage capacity. It is essential that operation rules be formulated with information that will be available at the time when operation decisions are made.

Fig.2.2(a) illustrates the combination of zones and rule curve levels that may define the operating policy of each reservoir in a multi-reservoir system. These reservoir operating policies permit some flexibility in multireservoir operation. A further aid in multi-reservoir operation is provided by identifying multiple subzones within the conservation zones. Fig.2.2(b) illustrates reservoir storage zones showing conservation zone with and without multiple subzones or levels (80).The volume within these levels can vary in magnitude, at a given time and overtime. Their main purpose is for multi-reservoir storage level balancing.

There are several parameters for reservoirs that should be specified to represent their physical characteristics and to describe the criteria under which they operate. It is necessary to provide storage content, surface area, outlet capacity, elevation levels,evaporation, seepage, exogenous inflows etc. In case of multireservoirs the releases should be made such that all reservoirs are kept in a relative state of balance.

The heuristic approach is to keep all reservoirs the same percent full within each zone. In some cases it may be desirable to use a certain portion of the conservation storage in one reservoir before using the storage of other reservoirs.

2.4 Releases from Combinations

Using the zoning concept for reservoir operation, all reservoir storage volumes should be maintained in the same zone or subzone to the maximum extent possible. There are three basic concepts for such balancing of reservoir storage volumes. The first concept is based on keeping all reservoirs at their same zonal position, i.e. at a level where the percentage filling of the zone is equal for all reservoirs. This is sometimes referred to as the equal function or equal index policy. The second concept is based on a reservoir ranking or priority concept. The entire zone of the lowest ranking reservoir is utilized fully before starting on the next lowest ranking reservoir, and so on. The third concept is based on a storage lag policy. Withdrawals from the zones of some reservoirs are begun before withdrawals

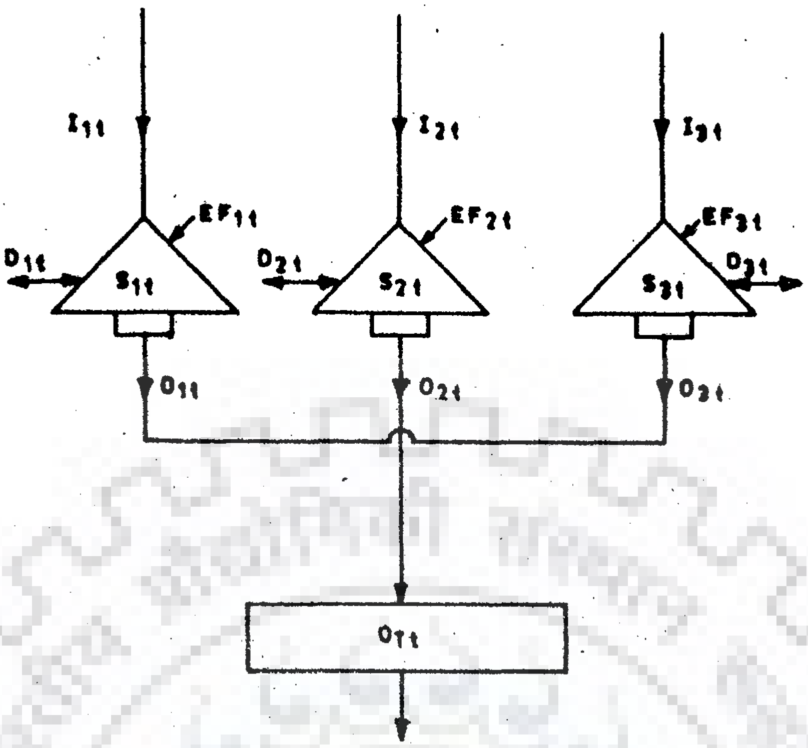


FIG. 2·3-PARALLEL RESERVOIRS

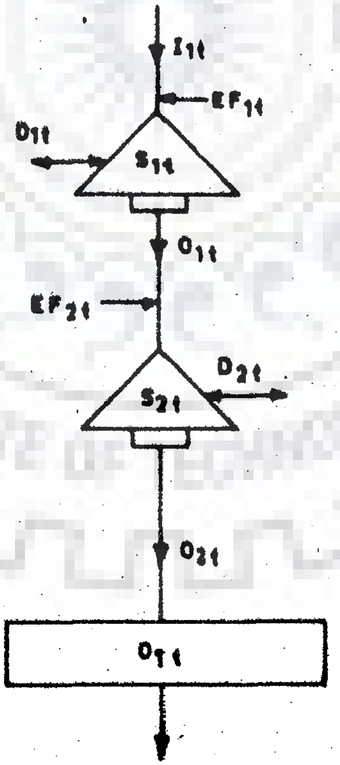


FIG. 2·4 SERIES RESERVOIRS

SE_{it} = Storage within the conservation zone at the start of time period t

I_{it} = Stream inflows excluding exogenous flows

EF_{it} = Exogenous inflows

O_{it} = Releases from the i^{th} reservoir at time period t

D_{it} = Gains and losses (rains, flow to stream, seepage and evaporation losses).

For three reservoirs in parallel, index levels in two reservoirs to be same.

$$S_{1t} \times SI_{2t} = S_{2t} \times SI_{1t}$$

and $O_{2t} = OT_t = O_{1t} - O_{3t}$

$$S_{1t}\left(SE_{2t} + I_{2t} + EF_{2t} - O_{2t} \pm D_{2t}\right) = S_{2t}\left(SE_{1t} + I_{1t} + EF_{1t} - O_{1t} \pm D_{1t}\right) \quad (2.4)$$

$$S_{1t}\left(SE_{3t} + I_{3t} + EF_{3t} - O_{3t} \pm D_{3t} \right) = S_{3t}\left(SE_{1t} + I_{1t} + EF_{1t} - O_{1t} \pm D_{1t}\right) \quad (2.5)$$

$$\therefore \frac{S_{2t}}{S_{3t}} = \frac{\left[SE_{2t} + I_{2t} + EF_{2t} - (OT_t - O_{1t} - O_{3t}) \pm D_{2t}\right]}{\left(SE_{3t} + I_{3t} + EF_{3t} - O_{3t} \pm D_{3t}\right)} \quad (2.6)$$

$$S_{2t}(SE_{3t} + I_{3t} + EF_{3t} \pm D_{3t}) - S_{2t}O_{3t} = S_{3t}(SE_{2t} + I_{2t} + EF_{2t} \pm D_{2t}) - S_{3t}(OT_t - O_{1t} - O_{3t})$$

$$S_{3t}(OT_t - O_{1t} - O_{2t}) - S_{2t}O_{3t} = S_{3t}(SE_{2t} + I_{2t} + EF_{2t} \pm D_{2t}) - S_{2t}(SE_{3t} + I_{3t} + EF_{3t} \pm D_{3t})$$

Let

$$K_2 = SE_{2t} + I_{2t} + EF_{2t} \pm D_{2t}$$

$$K_3 = SE_{3t} + I_{3t} + EF_{3t} \pm D_{3t}$$

$$-(S_{3t}+S_{2t})O_{3t} + (OT_t-O_{1t})\,S_{3t} = S_{3t}\,K_2 - S_{2t}\,K_3$$

$$O_{3t} = \frac{S_{3t}\,(OT_t-O_{1t}-K_2) + S_{2t}K_3}{(S_{3t}+S_{2t})} \qquad (2.7)$$

Again similarly,

$$S_{2t}(K_1-O_{1t}) = S_{1t}\,(K_2-O_{2t}) \qquad (2.8)$$

$$S_{2t}(K_3-O_{3t}) = S_{3t}\,(K_2-O_{2t}) \qquad (2.9)$$

$$\frac{K_1-O_{1t}}{K_3-O_{3t}} = \frac{S_{1t}}{S_{3t}}$$

$$(K_1-O_{1t})\,S_{3t} = S_{1t}\,K_3 - S_{1t}\,O_{3t}$$

$$S_{1t}\,O_{3t} = S_{1t}\,K_3 - S_{3t}K_1 + S_{3t}\,O_{1t} \qquad (2.10)$$

Substitute (2.7) in (2.10) and simplify

$$\frac{S_{1t}\,S_{3t}\,(OT_t-O_{1t}-K_2) + S_{1t}\,S_{2t}\,K_3}{S_{3t}+S_{2t}} = S_{1t}K_3-S_{3t}K_1+S_{3t}O_{1t}$$

$$S_{1t}S_{3t}(OT_t-O_{1t}-K_2) = (S_{3t}+S_{2t})(S_{1t}K_3-S_{3t}K_1) + (S_{3t}+S_{2t})S_{3t}O_{1t} - S_{1t}S_{2t}K_3$$

$$\therefore S_{1t}S_{3t}O_{1t} + (S_{3t}+S_{2t})S_{3t}O_{1t} = S_{1t}S_{3t}(OT_t-K_2) - (S_{3t}+S_{2t})(S_{1t}K_3-S_{3t}K_1) + S_{1t}S_{2t}K_3$$

$$O_{1t} = \frac{S_{1t}S_{3t}(OT_t-K_2) - (S_{3t}+S_{2t})(S_{1t}\,K_3-S_{3t}\,K_1) + S_{1t}S_{2t}K_3}{S_{3t}\,(S_{1t}+S_{2t}+S_{3t})}$$

$$= \frac{S_{1t}(OT_t-K_2) - (S_{3t}+S_{2t})(S_{1t}K_3-S_{3t}K_1)/S_{3t} + S_{1t}S_{2t}K_3}{(S_{1t}+S_{2t}+S_{3t})} \qquad (2.11)$$

Similarly, we can find out O_{2t} and O_{3t} giving the releases from these parallel reservoir system.

2.4.2 Tandem reservoirs

In case of tandem system of reservoirs the downstream water requirements are met from the last reservoir however, other reservoirs above, supply the balance quantity may be equal to their inflows or the maximum power discharges. The last reservoir must be designed to have adequate storage capacity to meet the downstream desired releases. Fig.2.4 shows two reservoirs in tandem. Analysis in the following is done on the criterion mentioned in 2.4.1 of meeting OT_t by second reservoir releases and the releases of first reservoirs are equal to the stream inflows for second.

$$OT_t = O_{2t} \tag{2.12}$$

$$I_{2t} = O_{1t} \tag{2.13}$$

or

$$S_{2t}(SE_{1t}+I_{1t}+EF_{1t}-O_{1t}\pm D_{1t}) = S_{1t}(SE_{2t}+O_{1t}+EF_{2t}-OT_t \pm D_{2t}) \tag{2.14}$$

$$O_{1t} = \frac{S_{2t}(SE_{1t}+I_{1t}+ EF_{1t} \pm D_2) - S_{1t}(SE_{2t}+ EF_{2t}-OT_t\pm D_{1t})}{S_{1t} + S_{2t}} \tag{2.15}$$

However, due to the complexity involved because of a large number of system parameters, releases can not be determined if evaporation and hydroelectric demands are to be included in the analysis. This is so because the volume of water evaporated and the energy produced during the period depend on the average reservoir area and elevation of water respectively which are inturn related to the reservoir level. The average level depends upon the ending reservoir level which itself is a function of releases. Therefore, for the multiobjective analysis of the reservoir system an iterative procedure is required which assumes an ending reservoir level, calculates the volume of evaporation cost and the volume of water necessary to satisfy the energy demand, determines reservoir releases and computes a new ending reservoir level. This ending level is then used to recompute volumes of evaporation and water used for hydropower generation. The process is repeated untill values of the ending reservoir levels do not differ significantly.

2.5 Reservoir Operation Models

Different models have been used for evaluating alternate operating strategies. The operation policy prescribed in such models is limited by time steps considered. The operation policy considered in the planning stage suffers from the inability to consider the real time forecasts of streamflows. The time steps which can be incorporated at the operation planning stage can vary from on line to one year. In an optimization model the stochasticity of streamflows has to be incorporated explicit way where the statistical feature of historical data are used rather than the synthetic series preserving these statistical properties. In order to use the generated series in an optimization model an iterative procedure has to be adopted which iterates between a deterministic optimization model and a simulation model. The following operation models (102) are generally encountered by the researchers and application engineers.

Explicit stochastic optimization models have been used for evaluating reservoir releases by including probability distributions of inflows directly in deriving optimal releases policies. The application to a multi-reservoir system was carried out by Schweig and Cole (100). They applied dynamic programming to a two-reservoir system and found that computational costs were high even with very simplified inflow representations.

Implicit stochastic optimization models assume that there is complete information of future hydrologic inflows. After optimizing reservoir releases for the given sequence, appropriate regression analyses are performed on the simulated results to derive a reservoir release policy. Hall (39) and Young (119) had initiated the early work using this approach. Stochastic optimization models are difficult to formulate and always cross the limits of computational feasibility when more than two to three reservoirs are considered simultaneously.

Linear Decision Rule model was proposed by ReVelle et al. (95,96 and 97) to find the optimal operating rules. It requires the release to be a linear function of reservoir storage. As applied to reservoir operation, the form of this linear decision rule (LDR) is :

$$q = s - b$$

Where, q denotes the release during a period of reservoir operation, s denotes the storage at the end of the previous period and b is a decision parameter to be derived by the model to optimize a criterion function. Since its introduction in water reservoir management problems many modifications, extensions and discussions of the rule have been reported in the literature. Loucks and Dorfman (79) presented a comparative study of some of the existing forms of LDRs and proposed a LDR that was function of present storage volume and future inflow, the future inflow was assumed as known quantity. However, it had been indicated that the use of decision rule leads to conservative results. Joeres et al. (58,59) proposed a LDR which incorporated the correlation structure of seasonal streamflow and demonstrated it's capability of reducing the ranges of minimum and maximum releases and storages for the same reliability levels as compared to other existing forms of the LDR.

The main advantage in using LDR are in the resulting mathematical simplicity, vastly reduced computational burden. In order to use these models effectively, it may be required to simplify the system representation, to limit the length of the hydrologic sequence and to eliminate many detailed considerations which occur with operating multireservoir system in practice.

Trial and error approach using simulation models had been used (102) where several water-based benefits which were judged to be very difficult to quantify in economic terms.

2.6 Decision Variable Targets and Loss Functions

The form of loss functions and definitions of decision variable targets are central to any operation model development. These issues reported in the literature are discussed.

Unresolved questions regarding the best choice of a loss or benefit function for reservoir operation include the issues of convexity, concavity, or symmetry of the loss functions assumed. Stedinger (105) has argued that penalization of releases in excess of the target value is unrealistic. However, according to Klemes (65), a release target may be defined either as a scale of development (the release in excess of this target value generates benefits, failure to meet this target value is associated with economic penalities) or as a value which causes no losses (the value corresponding to the minimum of the loss function or maximum of the benefit function). When the second definition of a target value is accepted, it is possible to assume the loss to be zero (or a constant) in the vicinity of the target, implying no losses for small deviations from this particular value.

If the only objective of operating a reservoir, or reservoir system, is to ensure a dependable flow during dry periods and other objectives are ignored, it is possible to adopt a loss function which constitutes only the dry branch of a two sided generalised loss function. A two-sided loss function may be necessary when multiple objectives, e.g. recreation and hydropower are important.

It was pointed out by Klemes (64,66) that considering a loss function L (y) = Y^{a}, where y is the outflow from a single reservoir (with mean E(y), E(.) is the mathematical expectation), for a convex loss function ($a < 0$ or $a > 1$) a sequence of variable releases. For a concave loss function ($0 < a < 1$) a variable release is superior to a constant release. For a linear or a constant loss function ($a = 1$ or $a = 0$), the overall economic effect is independent of the outflow pattern. Accordingly, it may seem that no general optimization is possible for the last two cases. It should also be noted, however, that these conclusions are based on restrictive assumptions.

Klemes (66) stated that, when uncertainties are incorporated into an operation policy, the releases of a target draft (the release at which the loss function has its minimum) should be the objective of operation. Once this is accepted, the objective of operation may be considered as the minimization of expected losses, where the short-term loss function is a function of deviation from the target release instead of release only. If y is redefined as (release - target) the conclusions for the previously defined y are no longer valid. E(y) may not be guaranteed as a positive quantity and the validity of the conclusions for different ranges of the exponent, a, therefore, depend upon the choice of the target value.

Stedinger (105) showed that for $a = 2$, and y =(release-target), the expected value of the losses is a minimum when the target is equal to the mean flow for the same given period.

This result is no doubt true, the question that needs to be answered, however, is : is it possible to meet practically this ideal operating criterion without perfect hydrologic information and/ or building a large (semi-infinite) reservoir. Stedinger's result also means that if the effective target release is equal to the expected value of the streamflow, the long-term expected losses will be a minimum. It is not clear, however, that an expected value criterion is always appropriate.

Theoretical target reservoir releases, shown schematically in Figure 2.5 have been defined in two ways. The first concerns a value, X_{min}, guaranteed with high reliability, for short-term allocation. For a release equal to X_{min}, short term allocation or for a release equal to X_{min}, short-term benefits equal long-term benefits and no penalities are incurred. Releases in excess of X_{min} give rise to increase benefits, although these benefits are lower than could have been attained (from the long-term benefit function) had the guaranteed amount been higher. The long-term benefit function, should start dipping down at some value of reservoir releases, X^+, when an incremental release will cause a problem such as flooding, damage to aquatic life, or loss of recreational opportunity. The short-term benefit function will also dip down but for a corresponding release $X < X^+$, except for the unusual case of X_{min} coinciding with X^+ in which case $X=X^+$. (The long-term benefit function is the envelope of short-term benefit functions).

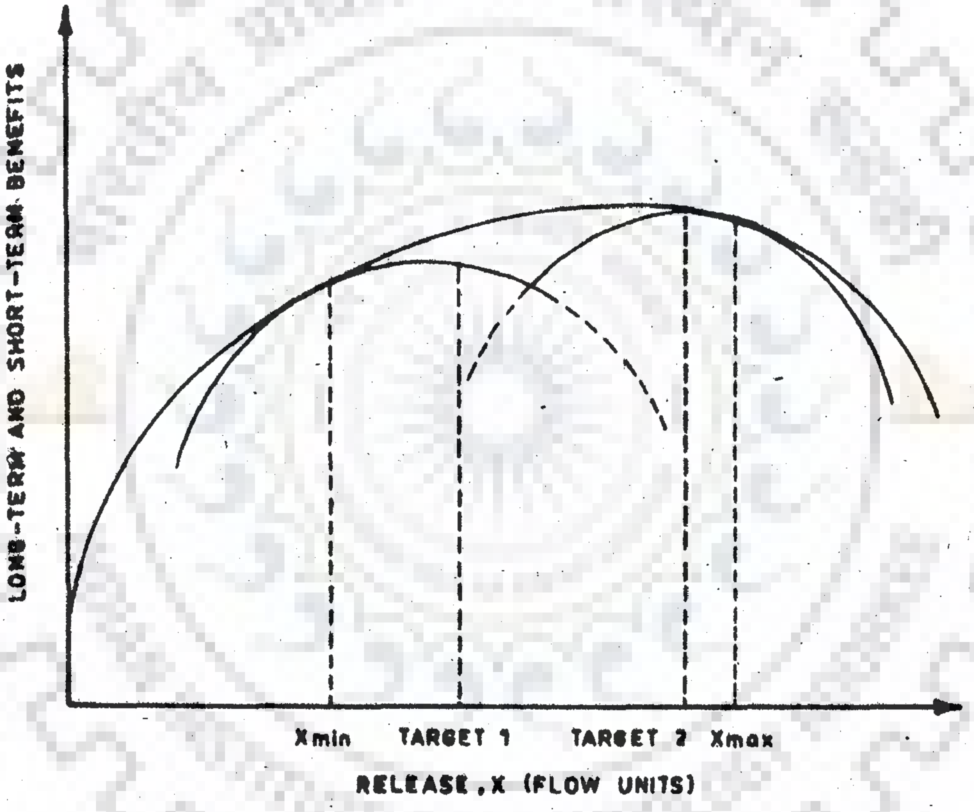


FIG. 2.5 THEORETICAL TARGET RESERVOIR RELEASES

A second definition of target release could be developed using the release magnitudes, Target 1 and Target 2 shows in Fig.2.5. These values are treated as variables where short-term benefits are a maximum, i.e. penalties are zero, as defined by Klemes (65) (The benefit curves, viewed in the direction of decreasing benefits, are loss curves; short-term losses are at a minimum for releases Target 1 and Target 2) Selection of Target 1 or Target 2 is conditional on the objectives of operation. Target 1 is important for water supply objectives, Target 2 is associated with flood flow management.

The target value should be interpreted as that volume of water for which penalties are a minimum, any deviation from the vicinity of this value is penalized to whatever extent is appropriate. The exact shape of the benefit function will vary from basin to basin and may also be modified according to the perceptions of decision makers. Hashimoto et al. (47) wrote that loss functions of the type $L(X) = [(T-X)/T]^{\beta}$ for $X < T$, and $L(X) = 0$ for $X > T$, (X is the release, and T, the target release, β is a constant) when incorporated in an optimization model which minimizes the expected value of losses subject to some physical constraints, result in different types of policies depending on the value of β. They reported that the operation policy specified by the loss function for $\beta > 1$ results in hedging from the target release even if enough water was available. This does not occur for $\beta < 1$. This result can be visualized conveniently by examining the loss function $(T-X)^{\beta}$, shown in Fig.2.6. Let

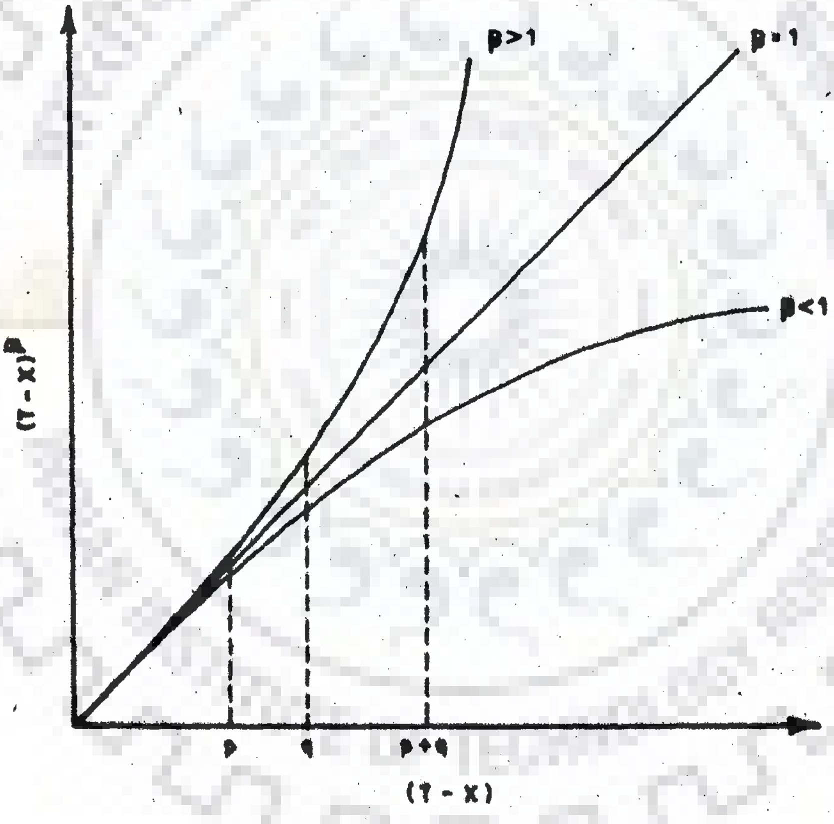


FIG 2·6 LOSS FUNCTION

p denote a possible deviation during period 2, and p + q the combined deviation at the end of the two operating periods.

It is evident that for an expected deviation equal to p at the end of period 1 and q during period 2, the losses can be minimized if the combined deviation is actually postponed upto the end of period 2, for $\beta < 1$. If $\beta = 1$, the delay does not affect the losses, and therefore may result in alternative optimum solutions. In thecase of $\beta > 1$, because $p^{\beta} + q^{\beta} < (p+q)^{\beta}$, it is always costlier to postpone the deviations and preferable to incur maximum losses at the first period, rather than adding them up for the second period. This conclusion is valid when using the expected loss criterion in the objective function because the transition probabilities (from one discrete flow state to another) used are assumed stationary and may be considered as constant multipliers to the loss magnitudes. Resilience another important index has been discussed recently by Fiering (24,25,26 and 27).

2.7 Reservoir Operation Objective Functions

In this section a few objective functions concerning with the reservoir operation are discussed. Warren A. Hall et al.(40) had considered objective function for deriving returns from operation by the sum of returns from expected sale of firm water and firm energy, dump water and dump energy for the price schedules given for each of the N time intervals. It was claimed that using the standard recursive procedures of dynamic programming a generalized equation could be written for successively for one

The authors had not presented the results but illustrated the procedure by developed technique for optimal analysis of a single multipurpose reservoir.

Theodore G. Roefs and Lawrence D. Bodin (109) for three reservoir system operation studies used the following objective function :

$$\text{Maximize} \quad \sum_{t}^{36} \left(Cp_t \, P_t + CU_t \, U_t + Cr_t \, r_{3.t}\right)$$

Where,

t	Time period in months
CP_t	Value of peak energy
CU_t	Value of off-peak energy
Cr_t	Value of release
P_t	Peak energy produced at time t
U_t	Off-peak energy produced at time t
$r_{3.t}$	Release from downstream reservoir at time t.

However, the implicit stochastic analysis process was not completed for the system with the observation that substantial repetition of lengthy computer analysis was required to achieve the results.

Determination of optimum operation policy for Folsom Project (North California) was the objective of Ricardo et al. (45). The objective function solved by dynamic programming was:

$$\text{Max AFE} = \text{Max} \left[\min_{n} \left(\frac{OE_n}{OPH_n} \; AOPH \right) \right]$$

Where,

AFE	Annual firm on-peak energy contract
OE_n	On-peak energy production in month n
OPH_n	Number of on-peak hours during month n
AOPH	Annual number of on-peak hours available every year
n	Time index, month

This type of objective function could not be used for complex systems.

The objective function applied by Chu and Yeh (17) for the hourly model given below was to maximize the daily power output from a single reservoir (Shasta Reservoir) :

$$\text{Maximize} \sum_{i=1}^{24} W_i \, P'_i \, (D_i , S_i)$$

Where,

i	time interval in hours
W_i	Weighting factors for each of the ith hourly generation
$P'_i \, (D_i, S_i)$	Power demand for ith hour
D_i	Plant release in ith hour
S_i	Storage at the beginning of ith hour

It is mentioned that convergence of the algorithm was extremely slow due to stepsize control problem. The Lagrangian procedures required two sets of initial solutions (primal and dual) and have several computational difficulties when applied to the practical problems. Multireservoir application is possible if overall convergence-problem could be handled appropriately. How to handle such problem was not indicated. It's application appears to be difficult.

Objective function to find a storage management schedule of a complex reservoir system which maximizes the system energy capability with acceptable uniformity in the surplus of power over load for each time interval was developed by R.H. Hicks et al.(49)

$$\text{Minimize } \left[F(S,Q) = D + W \sum_{j=1}^{J} (D_j - D)^2 \right]$$

where,

$$D_j = L_j - P_j$$

$$D = \frac{1}{T} \sum_{j=1}^{J} D_j T_j$$

$$T = \sum_{j=1}^{J} T_j$$

L_j	Total system load
$W > 0$	A suitable weight
P_j	Total power produced by system
S_j	Storage at the end of time interval j
T_j	The length of time interval j
J	Time interval

This was a remarkable accomplishment in the application of nonlinear programming to a practical engineering problem.

A method for the determination of optimal operating rules for a multiple reservoir and hydroelectric facility was outlined by Becker and Yeh (6) and illustrated by an application to California Central Valley Project. The objective function considered was :

$$\text{Minimize} \quad \sum_{K} \left(C_i^K \; R_i^K + C'^K_i \; R'^K_i \right)$$

K	Time index
R_i and R'_i	Variables to be determined
C_i and C'_i	Functions of energy rate function and average storage at any given time i and are known
i	Variable index

It had been claimed that the method could easily be adoptable to a variety of situations. However, the method was not extended to multireservoir operation problems.

George W. Tauxe et al. (106) applied Multi-Objective Dynamic Programming (MODP) for the operation of Shasta reservoir. Two specific objectives were considered : (1) To maximize the cumulative dump energy generated above a prescribed level of firm energy, and (2) to minimize the cumulative evaporation. The primary objective, that of cumulative dump energy, was maximized in recursive equation and secondary objective of minimization of cumulative evaporation losses was represented by a state variable. Firm energy maximization was formulated as a physical constraint on the two objective MODP problem and then parametrically varied outside the MODP problem.

$$F_j(S_j,V_j) = \underset{q_j}{\mathrm{Max}} \left[E_j\ (q_j,\ S_j,\ FE_j) \right]$$

Where,

F	Value of objective, also cumulative dump energy
E	Dump energy
ER	Rate of energy production
FE	Monthly firm energy requirement
V	Cumulative evaporation
S	Reservoir storage volume
q	Reservoir release
J	Stage and decision variable index

This work was considered to be extended for investigating risk as an objective and examining the trade-offs between risk and other problem objectives by the authors.

Optimization problem framed by David T Ford et al.(29) was to maximize f(x), the weighted sum of the efficiency indices. Ten indices of system operation efficiency were included in the given below objective function available for selection of the best operation rules for Rayburn reservoir system which included two reservoirs in series :

$$\text{Minimize} \quad f(x) = \sum_{K}^{P} W_K\ Z_K\ (x)$$

Where,

$Z_K(x)$	the value of index K of operation efficiency with decision variable x
P	the total number of indices
W_K	weight assigned to index K

$$\text{Max} \sum_i \left[V_i \left(x_i^K\right) + \Sigma\, C^K E\left(H_i \left(X_i^{K-1}, U_i^K \right)\right) \right]$$

Where,

$EH_i(X_i^{K-1}, U_i^K)$	Expected generation (MWH) of plant i in month K
C^K	Value of a MWH produced in the reservoir system
$V_i(x_i^K)$	Expected value of water remaining in reservoir at the end of last period studied.

It is mentioned that the solution is not a global feedback solution. The technique needs further application to real life systems.

In order to minimize total losses or damages resulting from the operation of single reservoir the following objective function (61) was considered.

$$\text{Minimize } Z = \sum_{t=1}^{T} \text{Loss} \left(R_t \right)$$

The following equations were used to define the loss function.

$$\text{LOSS} \left(R_t\right) = A \left[\exp \left(R_t/\text{RUP}\right) - \exp(1) \right]$$

$$R_t \geq \text{RUP} \qquad (1)$$

$$\text{LOSS}\left(R_t\right) = 0 \qquad \text{RLOW} \leq R_t \leq \text{RUP} \qquad (2)$$

$$\text{LOSS} \left(R_t\right) = B \left[\exp \left(-R_t/ \text{RLOW}\right) - \exp \left(-1\right) \right]$$

$$R_t \leq \text{RLOW} \qquad (3)$$

the hydro utility would purchase from the other utility.

Conjugate gradient method of modified Fletcher and Reeve's was used for one reservoir case. It could be used for multireservoir system with stochasticity in inflows.

It has been observed from the foregoing that the operation objective functions mostly considered maximization of power and/or energy, determiniation of optimal operating rules and minimization of total losses or damages resulting from the operation for single or multireservoir systems for monthly, daily or hourly time steps. A few of the models could be really useful for the analysis of large multireservoir systems.

CHAPTER III

BHAKRA-BEAS RESERVOIR SYSTEM OPERATION ANALYSIS

3.1 Introduction

Bhakra-Complex governs the system operation in the western part of Northern Power and Water Grid and meets the irrigation, energy and peak requirements of the power system. By addition of large peaking and energy capability in the Northern system in recent years, it is considered necessary to review present operations of the system and formulate how it will operate in the future so as to achieve marginal, short and medium term benefits. Description of Satluj-Beas River system projects (South Himalayan catchment) is briefly made and graphical representation is given in this Chapter. Hydrology of snowmelt and monsoon rivers typical for South Himalayan Catchments is then presented for inflow determination. So far, procedure followed by the system decision makers and regulating engineers for water releases from Bhakra-Beas reservoirs to the canal system and power generation purposes is important for any study to be initiated. Studies reported on this system by research workers and others, comments on present operation and need for optimization study for working out operational alternatives are discussed herein. However, rescheduling operations do need separate analysis keeping in view power and irrigation requirements and unit commitment of Bhakra reservoir plants.

3.2 System Description

There are three major rivers in the region, Ravi,Beas and Satluj. Beas water are being transferred to Satluj basin to maximise the irrigation and power potential of the two river basins. Figs. 3.1 and 3.2 give detail of the system. A total of over 2 million hectares would be irrigated finally in Punjab, Haryana and Rajasthan.

The projects on two rivers are briefly outlined below :

3.2.1 Projects on river Satluj(22)

i) Concrete gravity dam at Bhakra

ii) Bhakra Power Houses (Plant-I and II) at the toe of dam on both the banks

iii) Nangal Dam (Barrage) at Nangal

iv) Nangal Hydel Channel

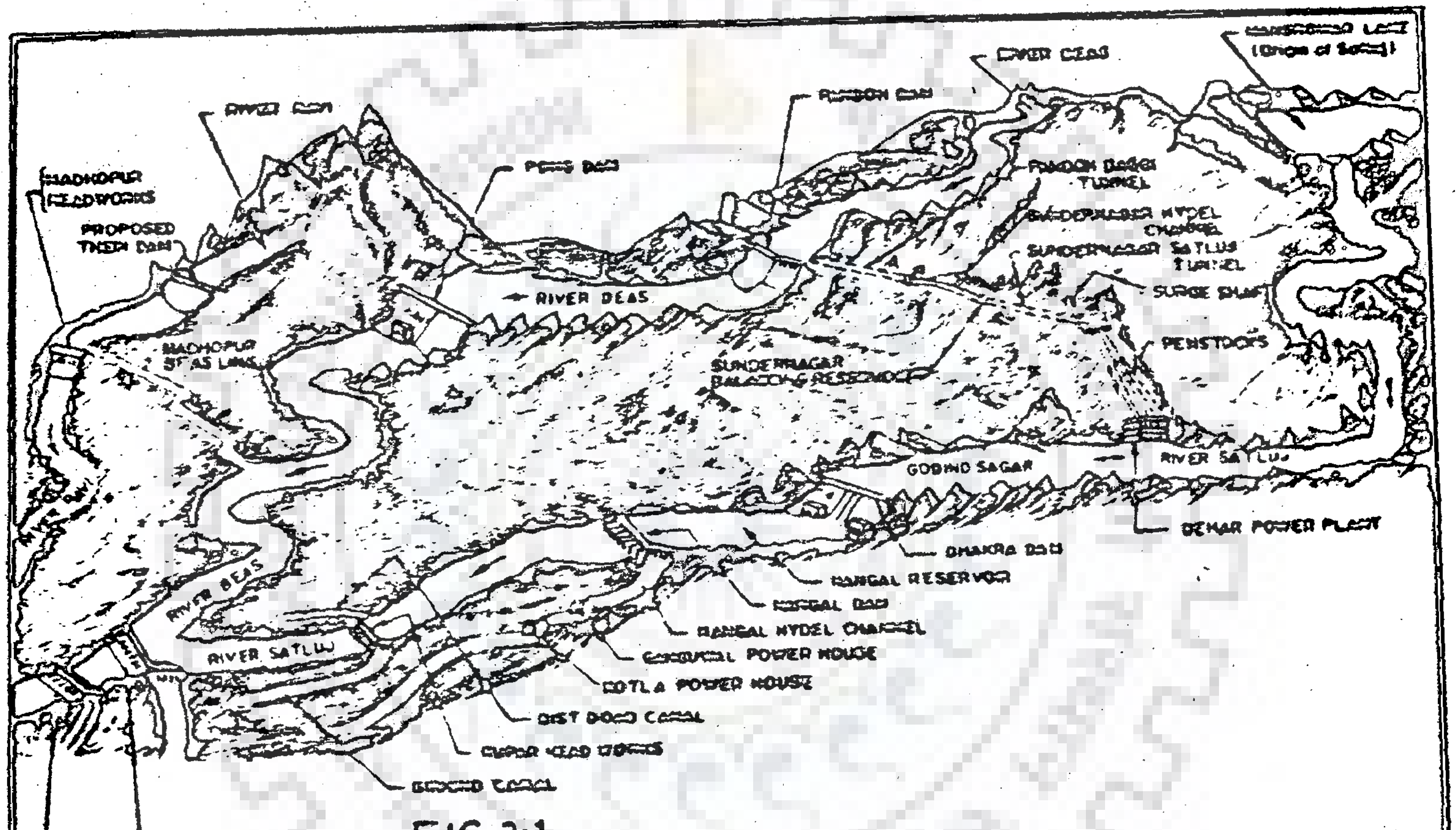
v) Ganguwal and Kotla Power Houses on the Hydel Channel

vi) Ropar Head Works and Sirhind Canal

vii) Bhakra Canal after tail waters of Kotla Power House

viii) Bist Doab Canal taking off at Ropar, Right Bank of Satluj river

ix) Anandpur Sahib hydel channel under construction



FIG·3·1
RESERVOIRS, POWER PLANTS AND CANAL SYSTEM
ON SATLUJ, BEAS & RAVI RIVERS

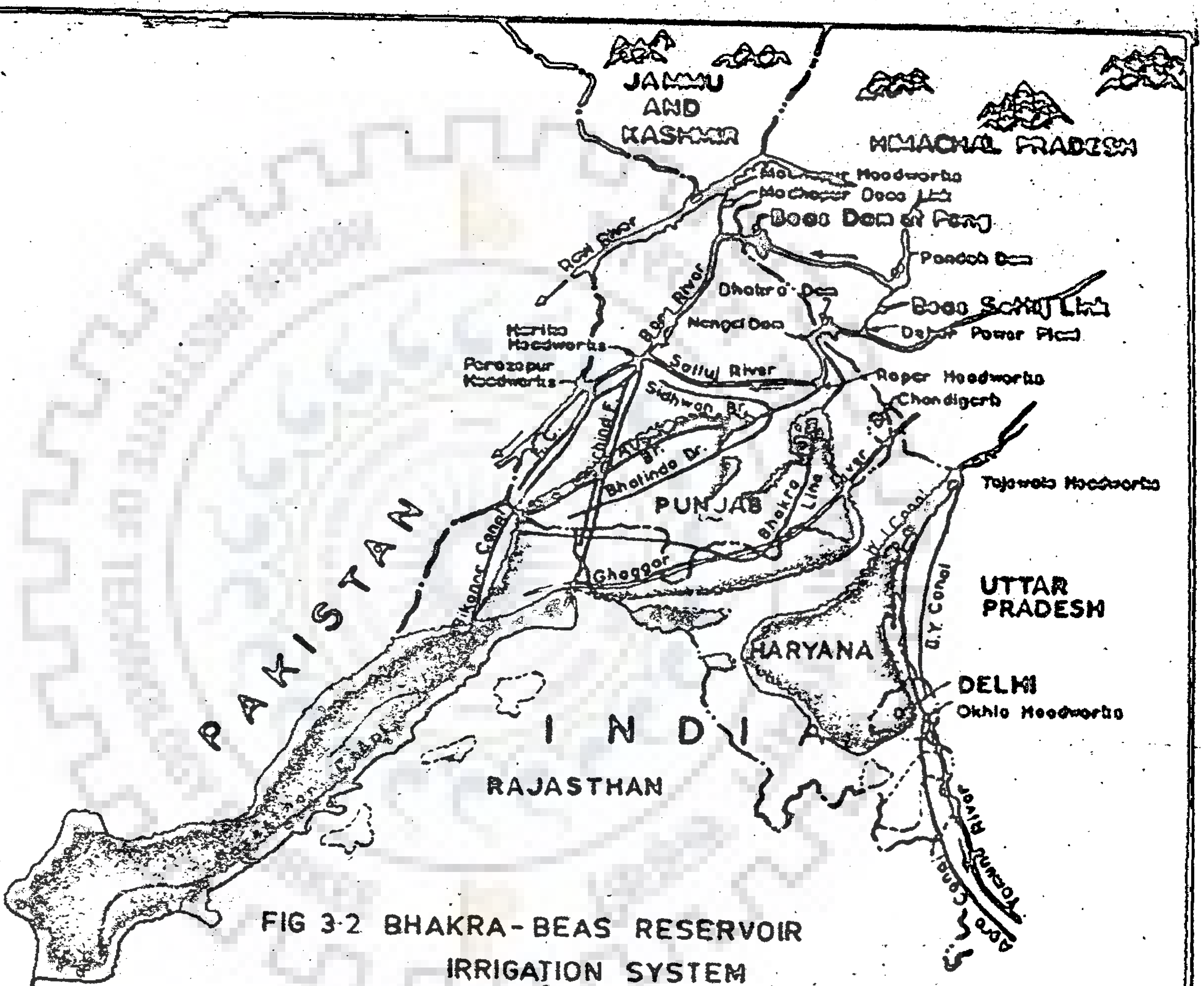


FIG 3·2 BHAKRA-BEAS RESERVOIR IRRIGATION SYSTEM

Bhakra reservoir gross capacity is 9876 m.cum. and live 9436 m. cum. with power production capacity of 1050 MW, in two power plants. The reservoir levels vary from 155.06 to 89.69 meters causing generating capability variation. About 11 Km. downstream of Bhakra dam is Nangal reservoir formed by the 28.95 m high Nangal dam. It serves as a head regulator for control of irrigation releases. Part of the water from Nangal is released to Nangal Hydel Channel with a carrying capacity of 353.75 cumecs. The remainder of the water is released to Satluj. The Nangal hydel channel supplies water to two power houses on its path at Ganguwal and Kotla with a total installed capacity of 154 MW. Water from the Nangal hydel channel is then divided between the Bhakra main canal and the Sirhind Canal (Fig.3.2).

Downstream of Nangal, there are headworks at two places on the river Satluj at Ropar and Harike (Fig.3.1). At Ropar water is diverted to BistDoab and Sirhind canals. The Beas river joins the Satluj at Harike. Water is diverted at Harike to the Rajasthan feeder and the Ferozpur feeder for Eastern and Bikaner canals and Sirhind feeder.

3.2.2 Projects on river Beas

Beas Project (7), (Fig.3.1)consists of the two units- one the Beas Satluj Link Project and the other the Beas dam project. Beas reservoir at Pong has live storage about 7290 million cubic meters which almost equals to that of Bhakra Dam. It is from this dam that Rajasthan State draws its major share of waters. The power house at the Dam will have six generators each of 60 MW capacity but only **four** have been commissioned.

The Beas Satluj Link Project which is basically a power project transfers 4716 m.cum. Beas water into Satluj through a height of 320 m and generating power. Diversion of Beas waters take place at a place known as Pandoh by creating a reservoir of capacity 4100 Hect. meters (33,240 acre feet). Beas waters are taken first through a 13.10 Km long tunnel and then through an open channel 11.80 Km. long to the balancing reservoir of capacity 370 hect. meters (3000 acre feet). Power Plant finally which will have 6 machines of 165 MW each is connected through 12.38 Km. long power tunnel to the balancing reservoir.

The graphical representation of the hydraulic and irrigation systems are given in Fig.3.3. Entire power of Bhakra-Beas complex is fed into the northern regional power grid. Interconnected power system is represented schematically in Fig. 3.4.

3.3 Hydrology of River Basins

It is typical of South catchments to receive heavy rainfall during the summer monsoon season generally extending from June to late September and sometimes even extending upto

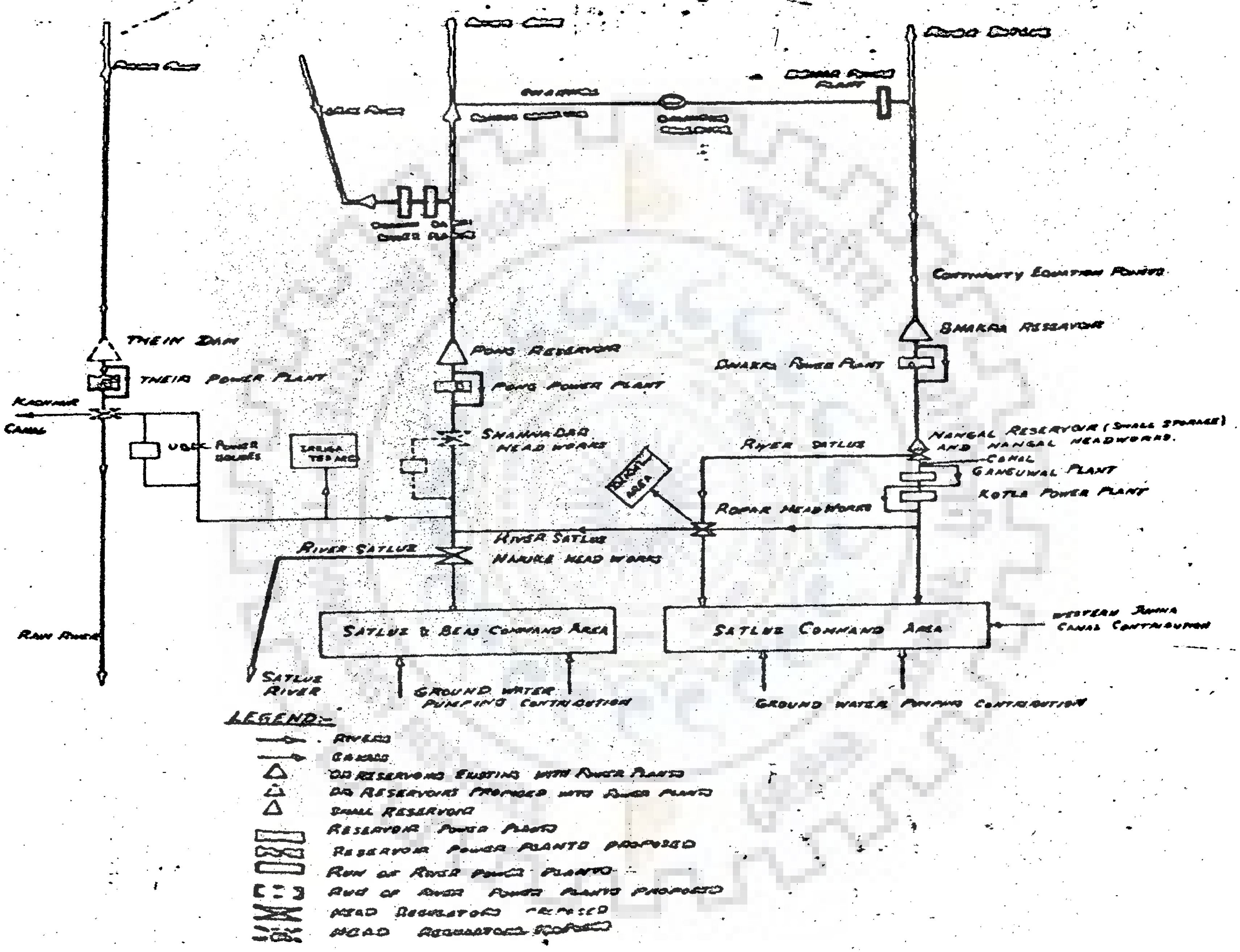


FIG. 3·3-GRAPHICAL REPRESENTION OF HYDRAULIC SYSTEM

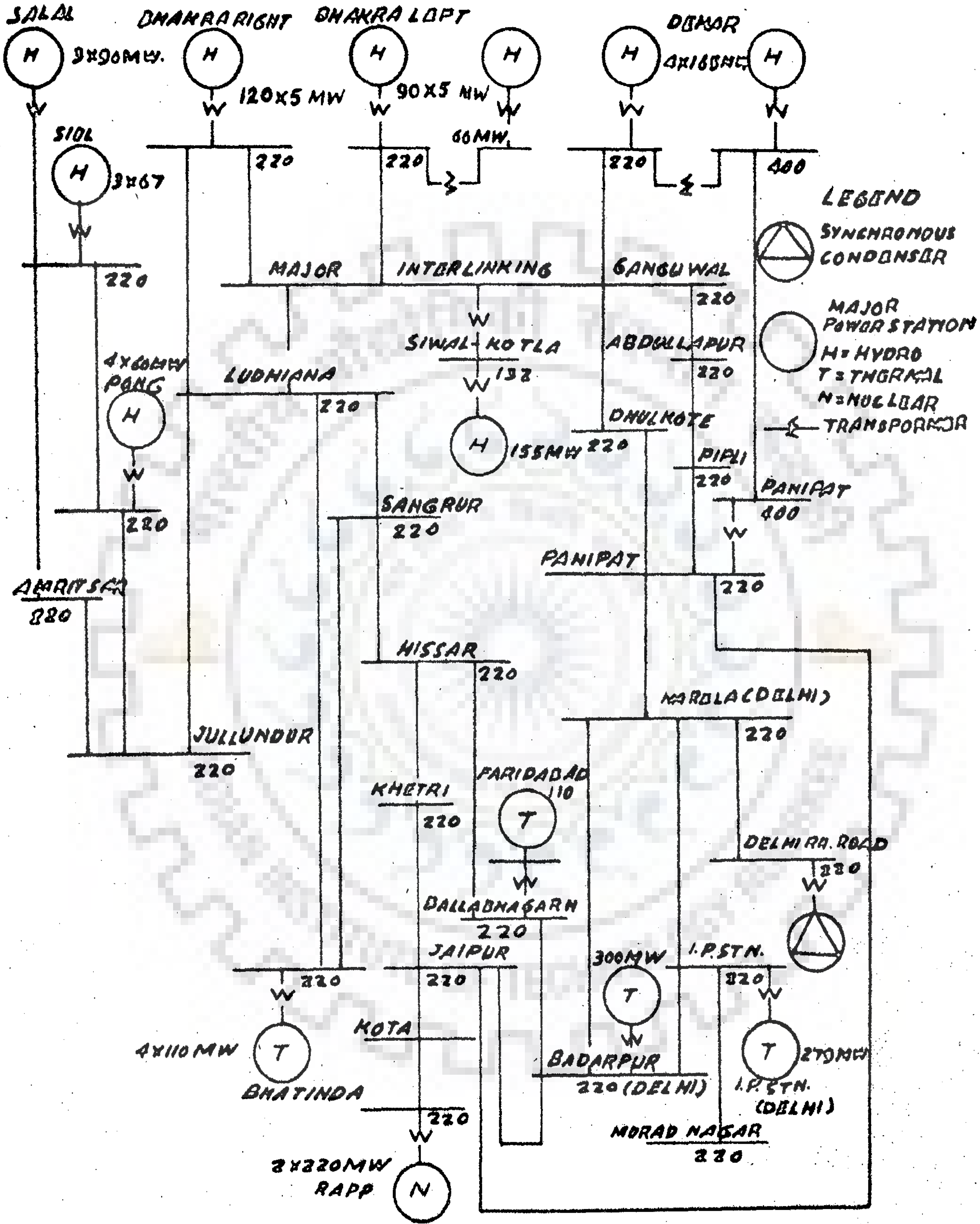


FIG.3.4 BHAKRA POWER PLANT & INTERCONNECTED GRID SINGLE LINE DIAGRAM 220KV AND ABOVE (Post Dehar)

the month of October. The river run offs basically consists of two parts, one which is derived from the melting of the snow and the other resulting from rainfall in the catchment. The discharge derived from the melting of snow, make the rivers parennial, its contribution to river discharge being greatest during summer months and minimum during winter. This part of the river flows is likely to be constant from year to year except for some changes caused by the annual variations in temperature conditions and extent of snowfall in the catchment areas. The average river discharges rise to considerable extent with the on set of monsoon season which generally lasts from June to September or sometimes upto middle of October. The high base flow is occasionally punctured by sharp peaked high flood flows of short durations during this period, the discharges and flood pattern being dependent on the intensity and extent of rainfall and its relative period of occurrence in the various sub-catchments upstream. Winter rains swell the river flows to some extent for short durations during the months of December, January or February when the river flow is usually at its minimum. The inflows of three rivers for a dependable year are given in Table 3.1(8). Filling-in-period is the period during which the flow of the river is more than the intended water requirements and the surplus flow is impounded to build up the storage. The period covers the monsoon season and does not include the period of high winter flows which may occur for short times. Bhakra

Table 3.1 Inflow of Rivers Satluj, Beas and Ravi in Cumecs for a Dependable Year

Month		River Satluj at Bhakra	River Beas at Mandi Plain	River Ravi at Madhopur	Total Inflow
June	11-20	707.5	360.5	312.3	1380.3
	21-30	857.9	420.8	327.1	1605.8
July		1233.4	918.7	513.8	2665.9
August		1293.9	1464.6	530.6	3289.1
Sept.	1-10	821.1	944.1	317.7	2082.9
	11-20	582.2	649.9	221.0	1453.1
	21-30	366.1	436.8	151.7	954.6
October		233.8	256.4	95.7	585.9
November		153.8	148.5	62.9	365.2
December		122.9	130.5	53.0	306.4
January		109.4	125.7	55.6	290.7
February		108.7	131.2	76.8	316.7
March		124.2	157.6	128.4	410.2
April		162.6	193.6	195.2	551.4
May		314.3	249.9	257.4	821.6
June	1-10	524.3	272.5	295.1	1086.9
Total inflow in million hectare metres		1.3723	1.2835	0.6713	3.3271

(After Bhalla and Bansal)

reservoir filling curves as contained in a project report (22) and being followed by operation planners are shown in Fig.3.5. The remaining part of the year outside the filling-in-period is considered as depletion period.

3.4 Present Procedure for Water Releases from Bhakra Reservoir

The water releases from Bhakra Dam are primarily to cater for the water indents at Nangal Dam which is the main regulating point for actual requirements of the areas covered under the Bhakra-Nangal Project. Thus the total water indents on Nangal Dam consists of (a) the requirement of Nangal hydel Channel which tails off into the Bhakra Main Line and (b) the requirement at Ropar Headworks with due allowance for losses or gains made in the length of river channel between Nangal and Ropar.

Normally, the water releases made for irrigation requirements would also cover the water demand for power generation purposes, but in some dry years, releases from Bhakra must have to be made from power consideration, when during specific periods firm power requirements cannot be met by the releases made for irrigation purposes only.

The extent to which the total water indents required at Nangal can be met from Bhakra depends upon the total available water, i.e. existing storage and the expected inflow of the Gobind Sagar (Bhakra Reservoir) during an year. In case

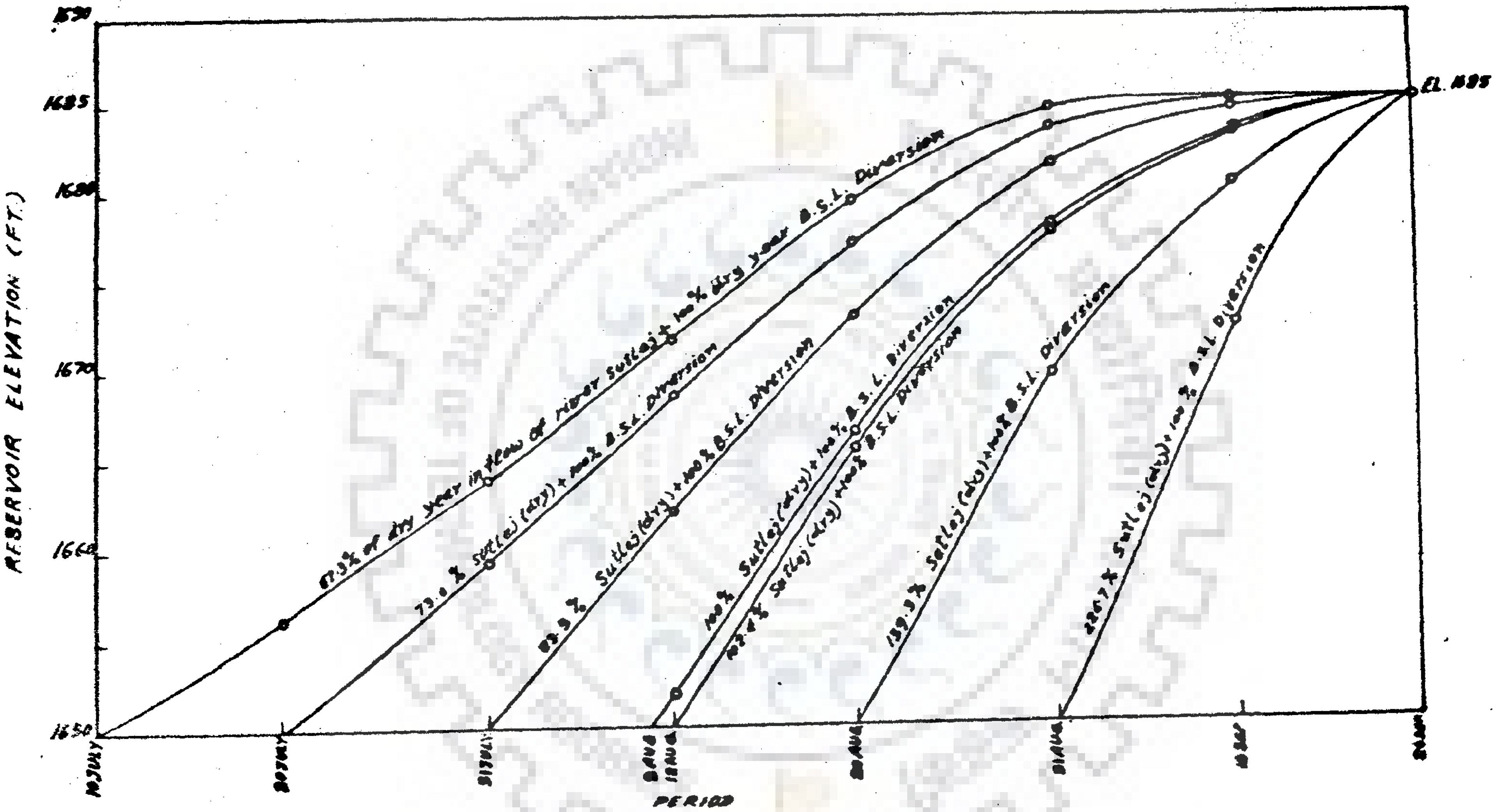


FIG.3·5 BHAKRA RESERVOIR FILLING CURVES

of the total available water falling short of the total requirements the indents at Nangal generally have to be suitably reduced before being met from Bhakra storage according to the reservoir factor (R.F.). The ratio of deliveries to demands is calculated as reservoir factor. The reservoir factor is evaluated from time to time during depletion period and it is equal to :

$$\text{R.F.} = \frac{\text{Available storage} + \text{Total river flow during the remaining period of the year}}{\text{Total water indent during the remaining period of the year}}$$

The water indents during depletion period are reduced by this factor before making the releases by system regulating engineers. It is observed that actual releases would depend upon the degree of accuracy to which the likely inflow during the depletion period can be estimated.

The procedure followed for meeting the water indents from Bhakra is (22) as follows :

i) to supply full water requirements during filling-in-period irrespective of the type of the year (above or below average)expected to be encountered.

ii) depending upon whether the year is going to be wet or a dry one, a suitable reservoir factor is estimated for the depletion period and releases made accordingly till the reservoir touches down the dead storage level after which only the run-off of the river is passed down to meet the indents.

In actual current practice reservoir factors are estimated more frequently during depletion period and minimum draw down level is being kept higher so as to get optimum irrigation and power benefits.

Surplus river flows and floods are disposed off with the help of river outlets and spillway. Above 1416 cumecs (50000 cusec which is considered as normal flow condition of river) the floods are categorized as low, medium and high floods above 4248 cumec i.e. 150,000 cusecs.

3.5 Resume of Earlier Studies

The question of filling up irrigation supplies gap and increasing the firm power capacity during short water period of Bhakra Complex had been discussed by Harbans Singh (46) long back. Apart from harnessing thermal and exploiting fully additional hydro resources, use of the tube wells had been emphasized for increasing firm power during May to October to help reduce water logging in certain areas and increase the irrigation potential. He indicated that tubewells should pump water into canals of Bhakra system to meet the irrigation requirements by supplementing releases at Ropar and Harike headworks which normally would be met by releases from the storage reservoir. By conserving equivalent amount of water in the storage reservoir Harbans Singh suggested that Bhakra releases could be purely according to power requirements, when releases for irrigation are lower than those required for power generation.

Minhas et al. (86) made probabilistic studies to determine the efficient combinations of irrigation and firm power which could be supplied with a given probability during the depletion period. They also, evaluated the extent by which irrigation and firm power could be increased through ground water pumping. They compared the present discounted cost of tubewell scheme with thermal back up. However, in the absence of a satisfactory economic measure of the relative worth of irrigation and power, definite operation strategy was missing. Effects of different dead storage elevations of Bhakra reservoir were also not analysed. Assumption of taking depletion period inflows as those of the driest year on record had been rejected. Due to difficulty in implementation, the study was not accepted by regulating engineers.

Amongst the general reporters, Mehndiratta and Hoon(84) of Bhakra Management Board reviewed Bhakra reservoir operation from 1967 to 1972. They compared anticipated and actual operation and pointed out that water releases for power demands overrode irrigation interests during the most of the months of the analysis period. The requirement of irrigation could be met from (i) river inflows (ii) Stored water in the Bhakra Dam (iii) contribution from Ravi, Beas and Yamuna rivers to Satluj Command Area. Average power generation during the six depletion periods varied from 315 MW to 455 MW. Power cuts were also started during this period as the power demand grew out of proportion in the months April, May and June. Carry-over storage served to reduce year to year fluctuations in firm power and irrigation levels. They observed that during Kharif maturing and Rabi sowing period (October to December), consumer of power get used to higher level of firm power, find it difficult to reduce their consumption in January and February when irrigation requirement reduces. In the end authors had pointed out that irrigation and power consumers of the region should be informed about the planned supplies and power availability during depletion period.

Lamba and Prem(69) indicated that the pattern of releases of water from reservoirs plays very important part in the overall development of the region. In their explanatory study for the integrated development of rivers Satluj, Beas and Ravi for optimum utility of water they concluded that if dead pond level periods of Bhakra and Pong reservoirs were staggered the average power in the grid was likely to rise from 920 MW to 953 MW thus giving an increase of 33 MW. However, the releases which had been assumed in these studies may not always be available thus it would be necessary to carry out studies for different conditions keeping in view the filling and depletion period of reservoirs. They further observed that since it had not been possible to coordinate the releases for irrigation and power in satisfactory manner, it caused low levels in the reservoir during the month of May when inflows were quite uncertain. Hence, the water power studies should be outlined at the start of the depletion period.

Bhalla and Bansal (8) calculated the effect of staggering the time of depletion of Bhakra and Pong reservoirs to their dead pond levels and concluded that this would increase the total minimum generation capacity of grid by 70 MW. Additional water for irrigation from December to April would also be available.

I.P. Kapila and B.S. Shishodia (60) described a computer simulation model which was formulated for the optimum utilisation of the Satluj, Beas and Ravi waters but due to inadequate analysis nothing had been recommended.

Rao (91) plotted transformation curves for reservoir factors and firm power for Bhakra reservoir by multiobjective framework solved by linear programming. Further for Bhakra-Beas system conjunctive utilization, problem was formulated for integrated management of surface and ground waters. It was concluded that level of irrigation and power planned for a dependable year could be attained in a dry year. However, for this system of irrigation and power utilization the study is exploratory. No comments on reservoir operation had been made except carry over storage. This study remains an academic exercise.

Latest attempt for Bhakra-Beas system was of Ranjodh Singh et al. (90) with power maximization objective and constraints in the form of inequalities in linear programme. This work was not extended beyond problem formulation.

From the foregoing examination, it is quite evident that little work has been done for Bhakra-Beas system operation optimization. After discussions with Member Irrigation and Member Power BBMB, it was revealed that there is a need for such study to work out several operational alternatives before selecting a particular water Power Study every year and updating each month.

3.6 Resume of Field Operations

The operation of the reservoirs on rivers Satluj and Beas is subject to contractual agreements between the participant states indicated in the original project report and some variations as agreed in the fortnightly/monthly, high level management meetings on actual water and power requirement basis.

The Management Board of this system conducts each year operational planning studies (known as water power studies) to regulate the supplies from Bhakra and Pong reservoir for meeting power and irrigation demands. Operation planning year from June 1 to May 31 is divided into two periods. June 1 to September 20 is the filling period during which snowmelt water and monsoon fills up the reservoir and September 21 to May 31 is the depletion period. Typical depletion curves are shown in Fig.3.5. Irrigation requirements are high in the months from September to November owing to water requirement for maturing of Kharif crops and preparation and sowing of Rabi crops.

Table 3.4 Bhakra Complex Generation in Million Units

Month/year	1967-68	1968-69	1969-70	1970-71	1971-72	1972-73	1973-74	1974-75	1975-76
April	282.1	334.5	325.3	395.6	305.7	413.9	319.7	402.7	314.5
May	343.6	375.8	395.8	393.9	269.9	492.9	406.3	426.6	385.9
June	326.6	351.7	412.2	355.8	335.7	421.5	492.7	325.5	377.3
July	327.9	344.4	419.9	374.3	374.9	446.4	575.3	371.3	491.0
August	326.7	354.7	443.7	311.5	385.7	368.8	576.2	372.2	509.7
September	322.2	395.1	435.3	314.3	447.9	380.7	588.5	353.9	572.0
October	340.0	359.8	435.8	395.9	497.8	350.8	509.5	307.5	515.4
November	332.7	380.6	429.1	406.5	464.9	387.0	510.3	299.1	523.7
December	328.9	389.5	435.6	378.7	460.1	349.5	505.7	277.6	537.0
January	344.7	376.7	402.5	322.0	444.0	314.8	467.2	246.9	458.4
February	332.0	316.3	383.9	290.0	392.0	286.6	413.0	239.6	410.1
March	331.9	364.7	464.3	342.0	453.0	329.9	448.0	300.9	475.1
Total	3939.6	4344.0	4983.6	4280.9	4832.0	4493.0	5811.9	3923.8	5569.1

Source : NREB, CEA, Ganguwal P.C.

Annual energy generation was about 4000 million units and maximum demand varied monthly. Monthly variation of energy and demands could be approximately divided into following four categories :

i) Maximum Generation and High Demand June 15-30, July, Aug., Sept. 1-15.

ii) High Generation and High Demand Sept.16-30, Oct., Nov., Dec. 1-10.

iii) Average Generation and Average Demand Feb.,March,April, May, June 1-15.

iv) Low Generation and Low Demand Dec. 11-20, January.

Generation/restricted load curves for the months of August and November, 1979 of Bhakra-Beas system and the entire system are given in Figs. 5.1 and 5.2 respectively. Looking at November, 1979 generation curve of Bhakra system, it is observed that the variation was similar to system changes. In other words the peaks and dips in Bhakra were as required by the system. In that case in whole of the system the major variations were taken by this reservoir plant. This type of peaking role was played in all other months except July, August and September.

August curve for 79 (Fig.5.1) is flat and generation of Bhakra system was 900 MW and the entire system 3750 MW. Since it was a monsoon month with adequate water, with less irrigation release problem, maximum generation was achieved. System peak was taken by steam plants in the grid.

3.7 Comments on Operation

It is observed from Sections 3.5 and 3.6 that Bhakra-Beas reservoir system had drawn the attention of field engineers and research workers continuously because of its complexity in operation and management and the important role it plays in the water-power grids.

Bhalla and Bansal (8) indicated change in the existing policy in their Water Power Operation Planning studies that these reservoirs should not be depleted simultaneously to their dead pond levels. From comparison of Tables 3.5 and 3.6 of their study it had been brought out in Table 3.7 additional water and firm power availability from December to April. More water was also proposed to be released from Bhakra reservoir than Beas hence depleting Bhakra reservoir earlier to Beas reservoir. This might result high Beas reservoir levels than Bhakra reservoir after the completion of filling period. However, these storages would depend upon the inflows during monsoon season.

However, little in concrete had been studied about the following :

1. Meeting energy and peak power optimaly for the system
2. Forecasting inflows, weather and power demands by latest techniques

Table 3.5 Releases and Power Generation

Month		Releases in cumec			Power in MW			
		Bhakra	Pong	Total releases at Bhakra and Pong	Bhakra	Pong	Dehar	Total
June	11-20	915.6	155.2	1070.8	620	64	530	1214
	21-30	1066.1	215.6	1281.7	724	87	530	1341
July		571.2	273.2	844.4	471	123	530	1124
August		527.9	273.2	801.1	574	153	530	1257
Sept.	1-10	725.1	512.3	1237.4	851	316	530	1697
	11-20	545.9	409.7	955.6	647	251	529	1427
	21-30	545.9	486.9	1032.8	644	297	527	1468
October		550.2	402.0	952.2	651	234	366	1251
November		310.5	809.1	571.0	173	197	941	1311
December		480.0	135.0	615.0	534	75	157	766
January		526.7	135.9	662.6	550	74	142	766
February		580.5	135.9	716.4	548	73	145	766
March		514.8	240.7	755.5	427	123	216	766
April		499.8	32.1	531.9	372	16	378	766
May		556.1	274.6	830.7	388	124	530	1042
June	1-10	738.9	212.4	951.3	509	86	530	1125

(After Bhalla and Bansal)

Table 3.6 Releases and Power Generation After Staggering

Month		Releases in cumecs			Power in M.W.			
		Bhakra	Pong	Total release	Bhakra	Pong	Dehar	Total
June	11-20	629.9	440.9	1070.8	460	190	530	1180
	21-30	790.2	491.5	1281.7	597	196	530	1323
July		571.2	273.2	844.4	515	119	530	1164
August		527.9	273.2	801.1	597	153	527	1277
Sept.	1-10	725.1	512.3	1237.4	867	319	525	1711
	11-20	549.9	409.7	955.6	658	251	522	1431
	21-30	545.9	486.9	1032.8	663	296	521	1480
Oct.		402.0	952.2	661.0	234	362	1257	1853
Nov.		498.6	310.5	809.1	591	173	196	960
Dec.		467.2	198.2	665.4	534	108	157	799
Jan.		594.7	22.4	617.1	645	12	142	799
Feb.		660.5	22.7	683.2	642	12	145	799
March		587.6	158.6	746.2	496	87	216	799
April		549.3	22.7	572.0	409	12	378	799
May		556.1	274.6	830.7	387	140	530	1057
June	1-10	564.7	386.6	951.3	394	176	530	1100

(After Bhalla and Bansal)

Table 3.7 Additional Releases at Bhakra in Cumec.

Month	Without staggering	With staggering	Additional water available with staggering
December	480.0	467.2	-12.8
January	526.7	594.7	68.0
February	580.5	660.5	80.0
March	514.8	587.6	72.8
April	499.8	549.3	49.5
Total additional Releases			257.5 cumec-month
Average Additional Releases			51.5 cumec-month

(After Bhalla and Bansal)

3. Optimization study of the multi-reservoir system operation
4. Re-evaluation and modification if necessary in the existing operation policies
5. Data based result oriented study for the consumptive use of ground and surface water
6. Unit commitment and generation scheduling
7. Application of automatic generation controls concept.

Optimization models for Bhakra and Beas system are formed in the ensuing chapters to study the above mentioned problems (except 2,5 and 7) with a view to analyse and improve the present operation. To facilitate this work or experimentation, multiobjective, multilevel nonlinear programme, nonlinear and mixed interger programme and iterative optimisation methods are used, followed by result analysis, discussions, conclusions and recommendations.

CHAPTER IV

BHAKRA-BEAS RESERVOIR SYSTEM OPERATION OPTIMIZATION STUDY

4.1 Introduction

Work reported on Bhakra reservoir system operation by the decision makers and regulation engineers is of general information nature indicating the sequential operation. Optimization study for Bhakra-Beas reservoir system planning had been taken up by a few (91,60,90). So far no work and publications are available on this system operation analysis and optimization. The necessity of present analysis is established and comments made in preceeding chapters. Consequently Bhakra-Beas system is modeled, details of applied solution technique are mentioned, results of four different studies analysed, discussed and operation guide lines suggested herein.

4.2 Problem Formulation

The approach of the problem model is based on multiple-objective optimization of the following type (21).

$$\text{Max } Z = C\,Z_1 - W\,Z_2$$

The first objective, Z_1 represents the worth of energy generation and is to be maximized. Z_2 represents second objective of minimization of maximum probable deviations from release targets. These objectives depend on the time and space distribution of the annual volume of natural runoffs to be received by the system. The weighting coefficients C and W have been introduced to allow a trade-off between energy and irrigation releases. If C = 1 and

W = 0, the model will maximize only the worth of energy. In case, if C = 0 and W = 1 the model will minimize the deviations from release targets.

This model is developed for use in system operation studies. The use herein is made for examining Bhakra Beas system operation schedules for received flow sequences. The model simulates the operation of this system by ten daily and monthly, sixteen time steps over the operation planning period. The reservoirs have a one year repetitive pattern. Since June to mid of September is the rainy season and prior to this these are to be depleted to absorb the maximum flood water for maximum energy generation and irrigation release objectives. Storage, inflows and outflows from the reservoirs and irrigation release targets have been assumed constants during each time step.

Fig.4.1 and 4.2 represent only Bhakra Beas System. Field operation achieved results- inflows, discharges, levels, power etc. for the period 1977-80, which could only be made available from the system regulation cells are given in Table 4.1, 4.2 and 4.3. It was necessary for the study to establish relationship between elevation and storage content of each reservoir. Gauss Newton Bard algorithm (68) has been used for curve fitting by taking the following function :

$$El - hm = a + b\, x^{c}$$

where

El	mean sea level
x	storage content
a,b,c	constants
hm	minimum level of reservoir

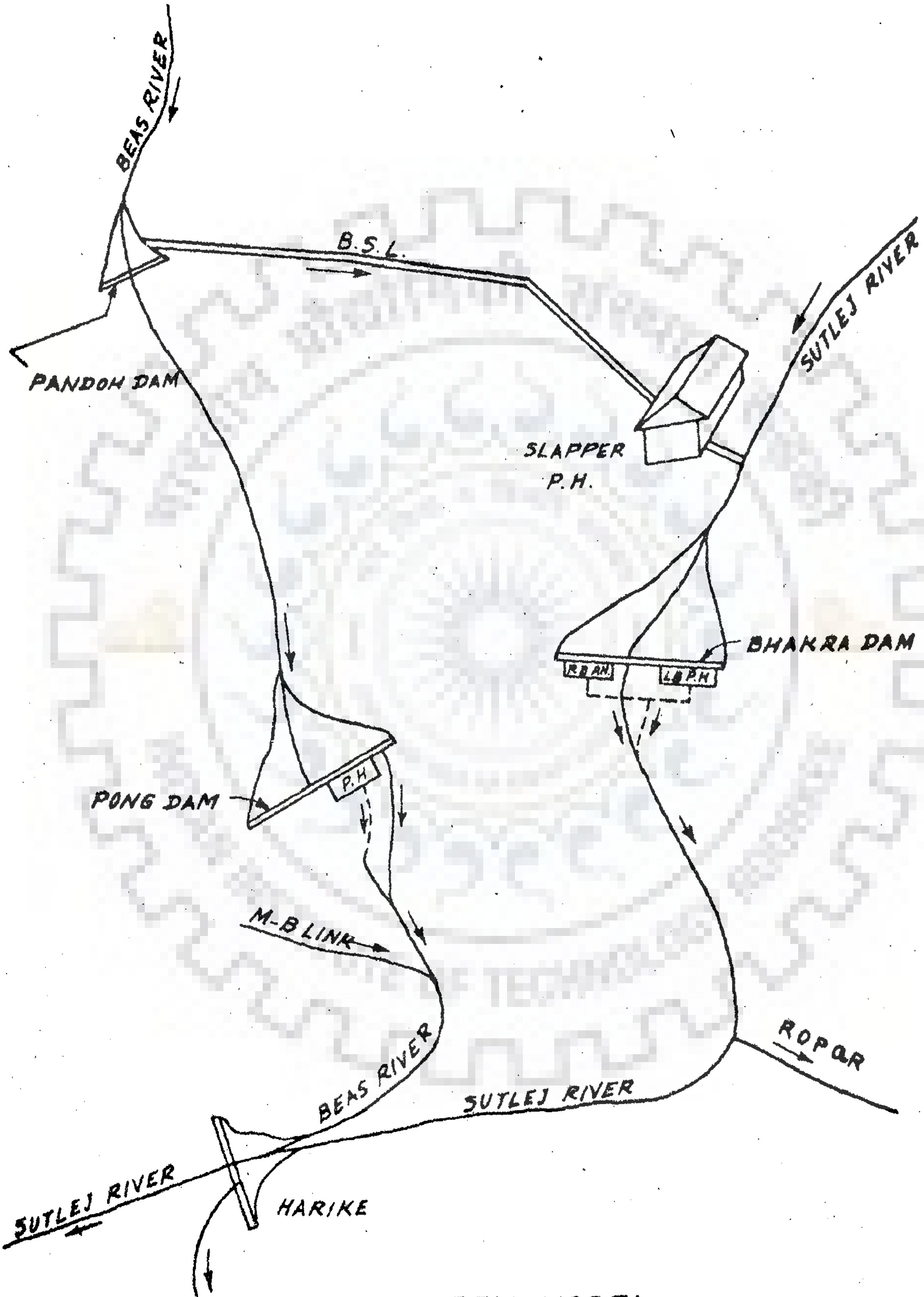


FIG. 4·2 SYSTEM MODEL

Table 4.1 Bhakra Beas Reservoirs System Field Operation Results for the Year 1979-80(Study 1 and 2)

Initial Storage Content 105928 cumec | Initial Storage Content 101690 cumec

Interval	Period	BHAKRA RESERVOIR						PONG RESERVOIR						Contribution from Ravi	Total Irrigation releases
		Satluj Inflows (cumec)	Power Discharge (cumec)	Spills (cumec)	Storage content (m^3)	Head (m)	Power Generated (MW)	Beas Inflows (cumec)	Power Discharge (cumec)	Spill (cumec)	Storage content (m^3)	Head (m)	Power Generated (MW)	(cumec)	(cumec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.	September (21-30)	607.00	591.65	0	[illegible]	154.66	628.00	180.51	360.00	320.50	97333	96.44	238.5	0.0	1272.15
2.	October	427.39	555.84	0	96407	154.66	590.58	180.74	360.00	68.10	89529	94.82	234.5	0.0	983.94
3.	November	301.27	582.41	0	87245	150.46	602.00	129.97	360.00	18.33	81843	92.17	228.0	0.0	960.74
4.	December	229.04	558.92	0	76170	145.26	557.80	124.65	351.78	0.00	77242	89.40	216.2	0.0	910.70
5.	January	203.74	549.21	0	66788	138.36	522.00	82.78	208.16	0.00	72559	87.70	125.5	0.0	757.37
6.	February	228.27	495.38	0	61103	131.86	448.75	168.61	335.16	0.00	72406	85.90	197.8	15.0	845.54
7.	March	307.37	519.18	0	56286	127.56	455.00	265.81	269.29	0.00	69105	85.90	158.8	29.2	817.67
8.	April	474.62	592.44	0	49684	123.66	503.30	219.80	284.53	0.00	67967	84.60	165.3	36.0	917.97
9.	May	433.63	660.82	0	44799	118.66	538.70	237.39	323.06	0.00	63732	84.00	187.0	195.1	1178.98
10.	June (1-10)	411.22	735.50	0	46725	114.16	571.90	164.99	360.00	40.17	62620	82.40	203.6	132.0	1267.67
11.	June (11-20)	814.14	663.00	0	57735	115.06	324.10	301.55	360.00	30.51	65842	81.90	202.5	132.0	1185.50
12.	June (21-30)	1829.29	724.50	0	72958	124.86	621.50	668.90	352.32	0.00	72943	83.20	201.4	132.0	1208.82
13.	July	1492.30	765.70	0	92619	136.19	716.40	873.71	360.00	44.00	89903	86.00	212.9	49.7	1219.42
14.	August	1215.90	669.00	0	99562	148.36	681.86	791.25	360.00	83.34	88755	92.30	228.3	26.0	1138.34
15.	September (1-10)	853.00	686.18	0	98812	152.16	717.30	315.55	360.00	185.00	84799	91.90	227.3	9.4	1240.60
16.	September (11-20)	591.50	654.08	0	95657	151.66	681.50	185.13	360.00	255.80	79457	90.50	223.8	0.0	1269.94

Table 4.3 Bhakra-Beas Reservoir System Field Operation Results for the Year 1977-78(Study 4)

Initial Storage Content 99969 cumec

Initial Storage Content 77566 cumec

Inter-val	Period	BHAKRA RESERVOIR						PONG RESERVOIR						Contribution from Ravi	Total irrigation releases
		Satluj Inflows (cumec)	Power dis-charge (cumec)	Spills (cumec)	Storage content (m^3)	Head (m)	Power generated (MW)	Beas Inflows (cumec)	Power dis-charge (cumec)	Spills (cumec)	Storage content (m^3)	Head (m)	Power generated (MW)	(cumec)	(cumec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.	September (21-30)	361.81	478.45	0	98712.5	151.82	499.02	446.40	360.00	221.17	75877	87.16	215.56	0.0	1059.0
2.	October	241.34	477.37	0	94107.0	149.31	489.66	273.72	360.00	119.59	72484	85.85	212.35	0.0	956.0
3.	November	182.61	565.17	0	83187.0	142.93	554.96	154.95	360.00	55.85	65886	83.20	205.77	0.0	980.0
4.	December	138.10	485.31	0	72084.0	135.72	452.50	112.68	360.00	17.18	56635	79.22	195.93	0.0	862 .0
5.	January	119.82	378.49	0	63035.0	129.16	335.85	145.55	360.00	67.07	48162	75.24	186.08	0.0	805.0
6.	February (29)	106.31	410.39	0	54749.0	122.46	345.26	139.17	360.00	75.13	39228	70.59	174.58	15.0	860.5
7.	March	101.02	529.70	0	43614.0	111.95	407.39	123.64	360.00	62.53	30156	65.22	161.28	29.2	981.0
8.	April	118.39	416.36	0	33057.0	100.01	284.95	159.63	315.62	0.00	23553	60.69	131.59	36.0	767.0
9.	May	186.71	414.71	0	25133.0	88.76	252.88	278.27	360.00	9.80	19916	57.89	143.17	195.1	980.0
10.	June (1-10)	470.70	396.97	0	24276.0	93.38	254.66	310.30	360.00	92.72	16831	58.28	136.71	132.0	981.0
11.	June (11-20)	303.28	406.14	0	23198.0	85.59	238.81	223.47	360.00	36.80	14830	53.44	132.17	132.0	934.9
12.	June (21-30)	823.61	481.90	0	26701.0	91.39	302.55	731.71	358.40	0.00	19072	57.20	140.84	132.0	972.3
13.	July	795.00	491.56	0	45395.0	113.85	384.47	1798.24	327.92	0.00	49411	75.85	170.87	49.7	869.0
14.	August	1357.62	464.65	0	76749.0	138.85	443.22	1684.77	360.00	215.92	94309	93.76	231.88	26.0	1066.0
15.	September (1-10)	1008.00	337.00	0	89011.0	146.41	338.95	1086.00	360.00	470.80	10080	95.91	237.20	9.4	1177.2
16.	September (11-20)	1072.00	438.00	0	95417.0	150.03	451.45	1113.50	360.00	661.61	101915	96.28	238.10	0.0	1414.6

The method and algorithm flow chart are given in Appendices I and II. Input data to the computer programme tabulated at Appendices III and IV.

The variables used are :

i	reservoir index $i = 1,2,3.....,I$
j	time interval index $j = 1,2,3,.....,J$
u_{ij}	the effective power discharge from reservoir i at time j. It is limited to the maximum hydraulic turbines rating u_{mi} and minimum discharge u_{ni} required from minimum tailwater considerations
$u_{(i+nr)j}$	the amount of water spilt from reservoir i at time j. The additional water bypasses the power house by flowing on the spillways.
nr	number of reservoirs. Herein two reservoirs-Bhakra and Beas have been considered.
F_{ij}	the natural inflow to reservoir i at time j
FT_{ij}	the total water inflow to reservoir i at time j $FT_{ij} = F_{ij} - (u_{ij} + u(i+nr)j)$ (4.1)
x_{ij}	reservoir i storage content at time j with the limitation of $x_{ni} \leq x_{ij} \leq x_{mi}$ According to mass conservation principle : $x_{ij} = F_{ij} - u_{ij} - u\,(i+nr)j$ (4.2)

$HP_i(x_{ij},u_{ij})$

The amount of electrical power generated by power plant i at time j. It is a function of effective discharge u_{ij} and water head $H_i(x_{ij})$. Also,

$$D_j + SR_j = HP_i(x_{ij}, u_{ij}) \tag{4.3}$$

where,

D_j and SR_j are electrical power demand and reserve requirement schedules to be met by Bhakra and Pong power plants.

R_{ij}	Irrigation releases from reservoir i at time j
RD_{ij}	Desired irrigation requirements from reservoir i at time j
W_i	Weighting coefficients
β_i	Coordinating variables
g_i	Computing constraints
r	second level multiplier
z	Objective function
k	Iteration or sub interval index in a particular time j.

The objective function formulation is based on two considerations firstly to analyse the system operation and secondly to make use the developed technique in the operation planning studies. For optimal operation of this system it is essential that the irrigation water releases from the two reservoirs meet irrigation targets fixed from time to time and satisfy the power demands scheduled by regional load dispatch centre. Hence, the below stated objective function has been framed keeping in view these requirements of the system and consists of maximization of power generation and minimization of deviations between released and desired irrigation water supplies ;

where A and B are square, constant matrices of dimensions (IJ, IJ) and $\bar{C}$ is a constant vector. Since matrix A is unit lower triangular, it is non-singular and the solution to $\bar{x}$ given $\bar{C}$ and $\bar{u}$ can be written :

$$\bar{x} = - A^{-1} (B\bar{u} + \bar{C}) \qquad (4.16)$$

Differentiating (4.16)

$$\frac{\partial \bar{x}}{\partial \bar{u}} = - A^{-1} B \qquad (4.17)$$

or

$$\nabla z = \frac{\partial z}{\partial \bar{u}} - B^T (A^T)^{-1} \frac{\partial z}{\partial \bar{x}} \qquad (4.18)$$

Knowing $\frac{\partial z}{\partial \bar{u}}$ and $\frac{\partial z}{\partial \bar{x}}$, the computation of Z is done in the following steps :

(a) Solve $A^T \lambda = - \frac{\partial z}{\partial \bar{x}}$ for λ (4.19)

(b) Calculate reduced gradient

$$\nabla z = \frac{\partial z}{\partial \bar{u}} + B^T \lambda \qquad (4.20)$$

4.4 Solution Technique

The operation problem of reservoirs having one year repetitive pattern is solved by multilevel hierarchial approach. This is based on the decomposition of large scale and complex systems and the subsequent modelling of the system into independent subsystems with its own goals and constraints, enables the analysis to understand the behaviour of the subsystems at a lower level and to transmit the information obtained to fewer subsystems at a higher level. The introduced new variables are called pseudo or coordinating variables. Then each subsystem is separately and if required independently optimized. Based on the nature of problem objectives and constraints, optimization techniques are then applied for solving the subsystems for the particular value of coordinating variables. This is the first level solution.

At the first level the Bhakra-Beas reservoir system problem is divided into sub problems of Bhakra-Beas reservoir system. The problem variables are converted into two groups i.e. dependent and independent variables. Storage contents of reservoirs are assumed as dependent variables and releases are considered as independent variables. Generalised reduced gradient technique is used to reduce the variables, reducing the size of problem, facilitating the equality constraints to be taken into account easily and eliminating the difficulty of arbitrarily choosing and adjusting penalty functions. The unconstrained problem of each subsystem is solved with the help of conjugate gradient technique. The subsystems are joined by coupling variables which are reservoir storages. The task at second level is to choose the coordinating variables in such a way that the independent first level subsystems are forced to choose solutions corresponding to an overall system optimum. The details of the approach are given in Fig.4.3 and mathematical representation is in the following :

water head $H_i(x_{ij})$. Also,

$$D_j + SR_j = HP_i(x_{ij}, u_{ij}) \tag{4.3}$$

where,

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$$\text{Min} \quad Z = \sum_{j=1}^{J} \sum_{i=1}^{I} \Big\{ \big[- HP_i \; (x_{ij}, u_{ij}) \; \big] + w_i (R_{ij} - RD_{ij}, 0)^2$$

$$+ \; w_i \big[(x_{ij} - x_{ni} \;)^2 \text{ or } (\; x_{ij} - x_{mi} \;)^2 \; \big] \Big\} \qquad (4.4)$$

Methods for solving nonlinear objective function and linear constraints for such problems in mathematical programming are available :

The general form of NLP

Minimize $f \; (x) \qquad x \in X \qquad (4.5)$

Subject to :

Linear and/or nonlinear equality constraints

$h_j(x) = 0, \; j = 1, \ldots\ldots, m \qquad (4.6)$

and (p-m) linear and/or nonlinear inequality constraints

$g_j(x) \geq 0, \; j = m+1, \; \ldots., \; p \qquad (4.7)$

The Lagrangian function is defined as :

$L \; (x, \; \lambda) \triangleq f(x) - \lambda \; g(x) \qquad (4.8)$

4.3 Gradient Calculations

The solution technique requires the gradient of Z. $\bar{u}$ and $\bar{x}$ are vector notations for discharges and storage contents in reservoirs and can be written as :

$$\bar{x} = \bar{x}_{ij} = (\; x_{01}, \; x_{02}, \; \ldots\ldots, \; x_{0j}, \; x_{11}, x_{12}, \ldots\ldots, x_{1j}, x_{I1}, \; x_{I2}, \; \ldots\ldots \; x_{IJ} \,)^T \qquad (4.9)$$

The vector $\bar{u}$ is similarly defined. The function Z can be written as :

$$Z = Z\ (\ \bar{u},\ \bar{x}\ ) \qquad (4.10)$$

The vector $\bar{x}$ is dependent upon $\bar{u}$ and can be written as

$$Z = Z\ (\ \bar{u},\ \bar{x}\ (\bar{u})\ ) \qquad (4.11)$$

$\frac{\partial Z}{\partial \bar{u}}$ denotes the partial derivative of Z with respect to u_{ij} with all other discharges and all contents treated as constants and elements are ordered accordance to equation (4.9).

$$\frac{\partial Z}{\partial \bar{u}} = \left(\frac{\partial Z}{\partial u_{01}},\ \frac{\partial Z}{\partial u_{02}},\ \ldots\ldots,\ \frac{\partial Z}{\partial u_{IJ}} \right)^T \qquad (4.12)$$

The partial derivatives of Z with respect to $\bar{x}$ are similarly defined.

Also :

$$\frac{\partial \bar{x}(\bar{u})}{\partial \bar{u}} = \begin{bmatrix} \frac{\partial x_{01}}{\partial u_{01}} & \cdots\cdots & \frac{\partial x_{01}}{\partial u_{Ij}} \\ \vdots & & \vdots \\ \frac{\partial x_{IJ}}{\partial u_{01}} & \cdots\cdots & \frac{\partial x_{IJ}}{\partial u_{IJ}} \end{bmatrix} \qquad (4.13)$$

Using the chain rule for differentiation, the gradient vector can be expressed :

$$\nabla z = \frac{\partial Z}{\partial \bar{u}} + \left[\frac{\partial \bar{x}\ (\bar{u})}{\partial \bar{u}} \right]^T \frac{\partial Z}{\partial \bar{x}} \qquad (4.14)$$

The relationship between $\bar{u}$ and $\bar{x}$ can be written in matrix forms as :

$$A\ \bar{x} + B\ \bar{u} + \bar{C} = 0 \qquad (4.15)$$

where A and B are square, constant matrices of dimensions (IJ, IJ) and $\bar{C}$ is a constant vector. Since matrix A is unit lower triangular, it is non-singular and the solution to $\bar{x}$ given $\bar{C}$ and $\bar{u}$ can be written :

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Knowing $\frac{\partial z}{\partial \bar{u}}$ and $\frac{\partial z}{\partial \bar{x}}$, the computation of Z is done in the following steps :

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(b) Calculate reduced gradient

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The operation problem of reservoirs having one year repetitive pattern is solved by multilevel hierarchial approach. This is based on the decomposition of large scale and complex systems and the subsequent modelling of the system into independent subsystems with its own goals and constraints, enables the analysis to understand the behaviour of the subsystems at a lower level and to transmit the information obtained to fewer subsystems at a higher level. The introduced new variables are called pseudo or coordinating variables. Then each subsystem is separately and if required independently optimized. Based on the nature of problem objectives and constraints, optimization techniques are then applied for solving the subsystems for the particular value of coordinating variables. This is the first level solution.

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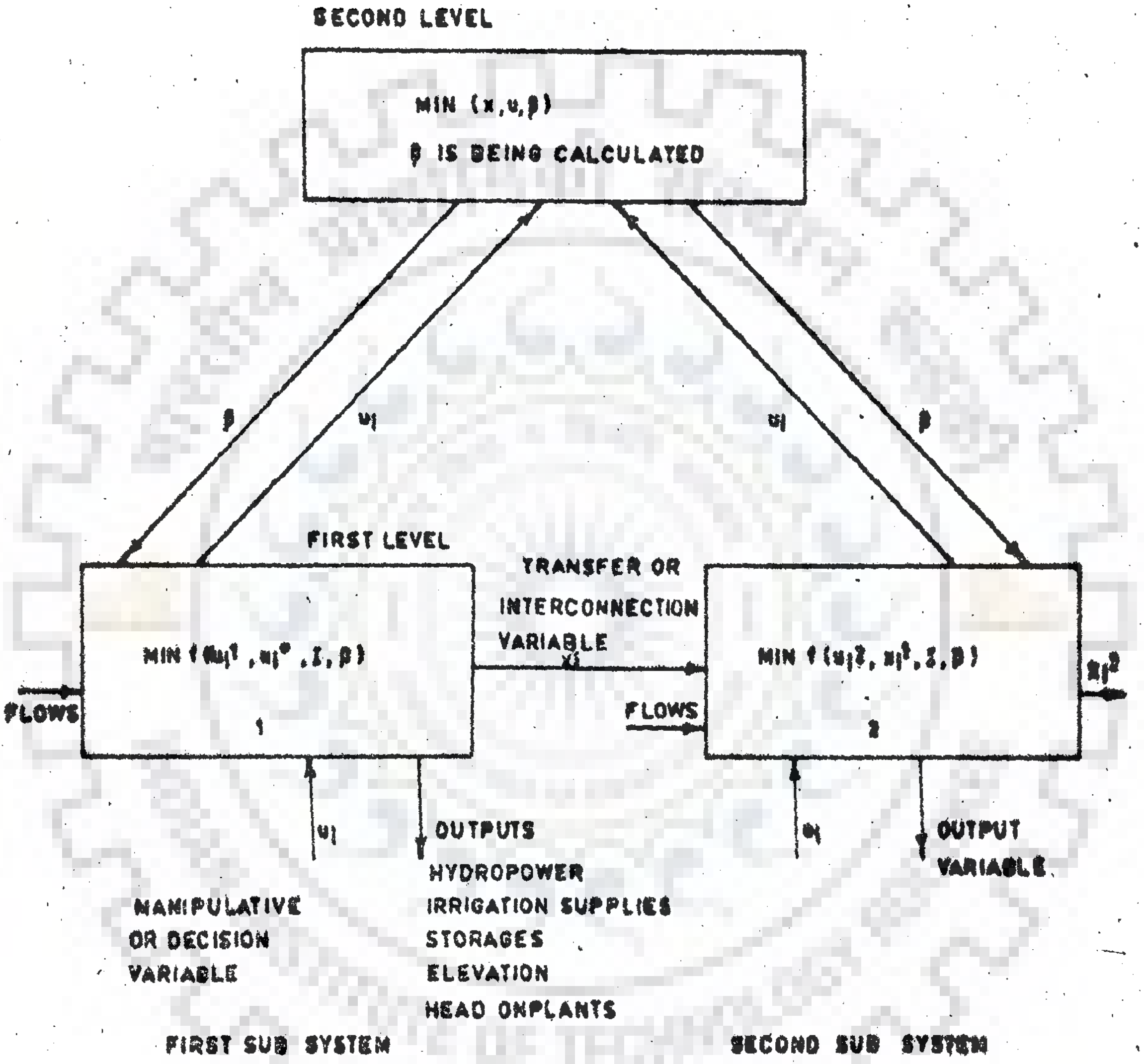


FIG 4·3 MULTI LEVEL EVALUATION PROCEDURE

4.4.1 Primal problem

$$\text{Min } Z = \sum_{j=1}^{J} \sum_{i=1}^{I} f\,(x_{ij}, u_{ij}) = \sum_{j=1}^{J} \sum_{i=1}^{I} \Big\{ \big[- HP_i(x_{ij}, u_{ij}) \big] + w_i (R_{ij} - RD_{ij}, 0)^2 + w_i \big[(x_{ij} - x_{ni})^2 \text{ or } (x_{ij} - x_{mi})^2 \big] \Big\} \qquad (4.21)$$

subject to :

Reservoir continuity constraint

$$A\,\bar{x} + B\bar{u} + \bar{C} = 0 \qquad (4.22)$$

Limits on reservoir variables

$$x_{ni} \leq x_{ij} \leq x_{mi} \qquad (4.23)$$

$$u_{ni} \leq u_{ij} \leq u_{mi} \qquad (4.24)$$

Coordinating constraint

$$g_i(\bar{u}) = \sum_{j=1}^{J} F_{ij} - u_{ij} - u_{(nr+i)j} = 0 \qquad (4.25)$$

4.4.2 Augmented problem

$$\min f(\bar{x}, \bar{u}, \bar{\beta}) = \sum_{j=1}^{J} \sum_{i=1}^{I} (x_{ij}, u_{ij}) + \sum_{i=1}^{I} \beta_i g_i\,(\bar{u}) \qquad (4.26)$$

Subject to :

$$A\bar{x} + B\bar{u} + \bar{C} = 0 \qquad (4.27)$$

$$x_{ni} \leq x_{ij} \leq x_{mi} \qquad (4.28)$$

$$u_{ni} \leq u_{ij} \leq u_{mi} \qquad (4.29)$$

4.4.3 Decomposed problem

Now the decomposed problem can be written as :

First level i^{th} subproblem

$$\min Z' = \sum_{i=1}^{I} \left[f(x_{ij}, u_{ij} + \beta_i g_i(u)) \right] \qquad (4.30)$$

Subject to :

$$A\,\bar{x} + B.\,\bar{u} + C = 0 \qquad (4.31)$$

$$x_{ni} \leq x_{ij} \leq x_{mi} \qquad (4.32)$$

$$u_{ni} \leq u_{ij} \leq u_{mi} \qquad (4.33)$$

Second level unconstrained minimization objective function :

$$\min_{\beta} f\,(x, u, \beta) \qquad (4.34)$$

$$\beta_i = \beta_{(i-1)} - \frac{r.\partial gi\,(\bar{u})}{\partial \beta} \qquad (4.35)$$

β is being chosen to minimize the difference between the total inflows and outflows at the end of the study period. It is being calculated by gradient methods i.e. by getting derivatives of total augmented function.

4.5 Algorithm

The basic steps of the method are :

i) Set time index $j = 1$ (4.36)

ii) Select vector $\bar{u}^{o}$, set iteration count or sub interval count $k = 0$ (4.37)

iii) Calculate x_j^k by solving equation

$$g(x^o,\ u_j^k) = 0 \tag{4.38}$$

iv) Calculate λ^k with the help of following relation

$$\lambda^{KT} = -\left[\frac{\partial f}{\partial x^k}\right]^T \left[\frac{\partial g}{\partial x^o}\right]^{-1} \tag{4.39}$$

v) Calculate λ with the help of following equation

$$\nabla f_u^k = \frac{\partial f}{\partial u^k} + \lambda^T \frac{\partial g}{\partial u} \tag{4.40}$$

vi) Calculate conjugate search direction

$$TD^k = \begin{cases} -\nabla f_u^k + \dfrac{(\nabla f_u^k)^T (\nabla f_u^k)\ TD^{k-1}}{(\nabla f_u^{k-1})^T (\nabla f_u^{k-1})} & k > 0 \\ -\nabla f_u^k & k < 0 \end{cases} \tag{4.41}$$

vii) Calculate projection of gradient on the bounds of independent variables :

$$S_j^k = \begin{cases} 0 & \begin{cases} \text{if, } \bar{um} - \bar{u}_j^k = 0 \text{ and } S_j^k > 0 \\ \text{if, } \bar{u}_j^k - \bar{um} = 0 \text{ and } S_j^k < 0 \end{cases} \\ S_j^k\ , & \text{otherwise} \end{cases} \tag{4.42}$$

viii) Calculate step size during quadratic interpolation such that $f\,(x_j^{k+1}\ ,\ u_j^{k+1}) < f(\,x_j^k\ ,\ u_j^k\,)$ and

$$\delta<\delta m = \min_j \left\{ \min_{S_j^k>0} \left[\frac{\bar{um} - u_j^k}{S_j^k}\right],\ \min_{S_j^k < 0}\left[\frac{u_j^k - \bar{um}}{S_j^k}\right] \right. \tag{4.43}$$

where

$$\bar{u}_j^{k+1} = \bar{u}_j^k + \delta\, S_j^k \tag{4.44}$$

ix) If $| f (x_j^{k+1} , u_j^{k+1}) - f (x_j^k, u_j^k) | \le \epsilon$ (4.45)

Go to step (x), otherwise go to step (iv)

x) Set $j = j+1$, if $j > J$ go to next step, otherwise go to step (iii)

xi) Calculate coordinating constraint (4.25), if $| g(\bar{u}) | \le \text{Tol}$, for all i, then stop, otherwise go to next step.

xii) β can be computed as follows :

a) Choose β at the second level

b) Optimize each of the subsystems at the first level

c) Correct β at the second level with the following expression

$$\beta_i = \beta_{(i-1)} - r \frac{\partial g(\bar{u})}{\partial \beta} , \quad r > 0 \tag{4.46}$$

d) go back to step (i)

The flow chart for this algorithm is given in Fig.4.4.

4.6 Results and Analysis

Results of four studies are discussed here. These studies pertain to :

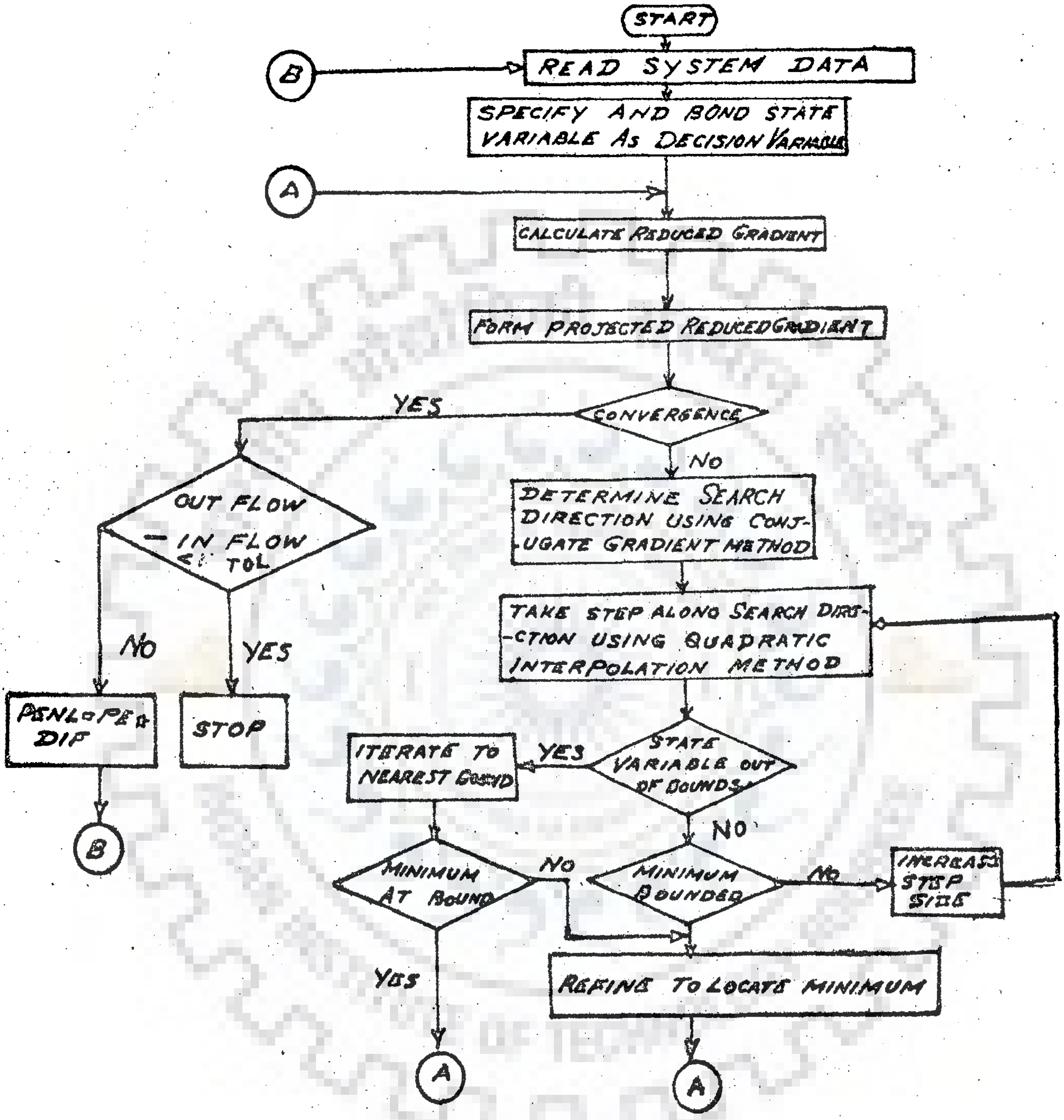


FIG.4·4 FLOW CHART OF NONLINEAR PROGRAMME

				Bhakra	Pong	Total
i)	Study - 1 Period-1979-80	a)	Initial Storage content (m^3)	105928	101690	
	Data-Table-4.1 Results-Table-4.4	b)	Average power generated(MW, 37.7 more than field achieved)			744
		c)	Irrigation releases (m^3 day, less than Study-2)	215994	122444	338438
ii)	Study-2	a)	Initial storage(m^3)	105928	101690	
	Period-1979-80 Data-Table-4.1 Result-Table-4.5	b)	Average power generated(66.2, more than field achieved and study-1)			772.5
		c)	Irrigation releases (m^3 days , field achieved were 357508)	236970	119587	356557
iii)	Study-3 Period-1978-89	a)	Initial storage content (m^3)	95417	101915	
	Data-Table-4.2 Result-Table-4.6	b)	Average power generated (MW). More than field achieved(788)			793.1
		c)	Irrigation releases (m^3 days, better than field achieved (462294) which are short in field by 7077)	257695	216495	474190
iv)	Study-4	a)	Initial storage content (m^3)	99969	77566	
	Period-1977-78 Data-Table-4.3 Results-Table-4.7	b)	Average power generated(MW, field 576.6)			559.2
		c)	Irrigation releases (m^3 days, field achieved 330132, includes spills from Pong 33822)	143637	189510	327147

The application of the solution technique to the reservoir system has been experienced a time taking process. The variables corresponding to storages have been eliminated thus reducing the size of problem. Intervalwise decomposition of the problem into subproblems and solution of the two objectives at two levels has greatly reduced the complexity of the system and computer memory requirements. Each study period consists of 16 intervals. The minimization of objective function (equation 4.30) results into a number of subintervals and steps. Variation in steps of various parameters, function, releases, power generated, squared target deviations and irrigation targets in a typical subinterval 1, interval 2 for study 1 are plotted in Fig.4.5. Used values of penalties, weighting coefficients and stepsize are also indicated in Fig.4.5. It is clearly indicated from the figure how sequentially the technique results into the minimum value of function and target deviations while maximizing power and meeting irrigation targets. Such results are also achieved for study 2 through study 4.

Apart from the above parameter variations, storage contents (x_1,x_2), turbine discharges and spills from reservoirs (u_1 through u_4) and stepsize variation during subintervals of three intervals for study 1 have been plotted in Fig.4.6. At the end of subintervals during each interval it is observed that irrigation targets are met which are sum of : ($u_1 + u_2 + u_3 + u_4 + GC_1$, turbine discharges and spills from Bhakra and Beas and contribution from river Ravi) and power is maximized. It may be seen how the step

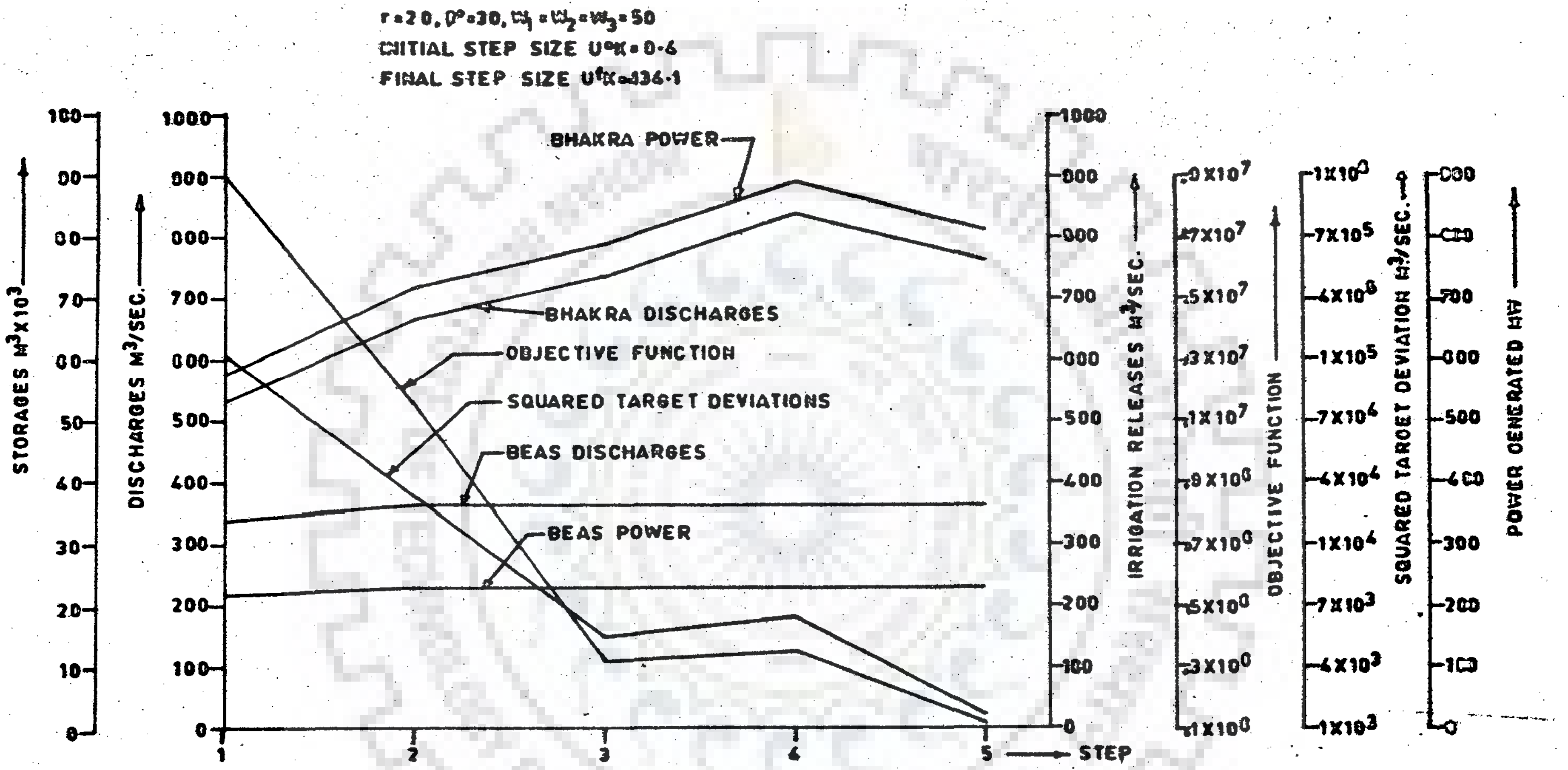


FIG. 4·5 VARIATON OF PARAMETERS IN FIVE STEPS OF SUBINTERVAL 1, INTERVAL 2, STUDY 1

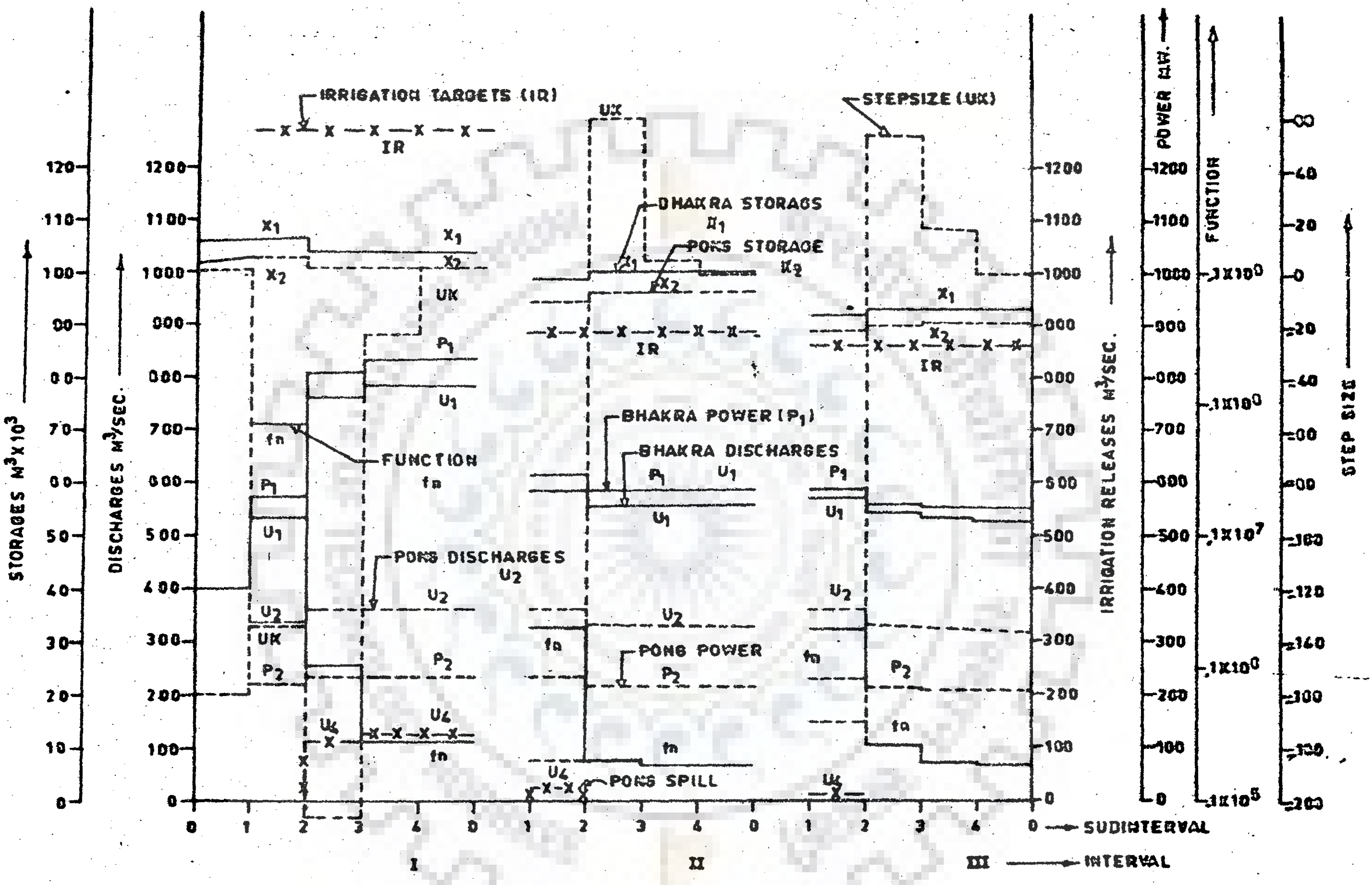


FIG. 4.6 VARIATION OF PARAMETERS IN SUBINTERVALS, INTERVALS OF STUDY 1

size finally reaches to certain definite minimum values during each subinterval as the function minimizes.

Optimization programme results for study 1 through 4 are listed in Table 4.4 through 4.7. Results for study-1 and 2 are also plotted in Fig.4.7 and 4.8. The following comments are made:

a) To meet the power maximization objective and irrigation requirements at Ropar and Harike points, studies indicated (Tables 4.4 to 4.7) that more water be drawn from Bhakra reservoir than compared to field achieved results (Table 4.1 to 4.3) wherein more water is released from Pong reservoir. From Fig.4.8 it is seen that in many periods released water (excess to turbine capacity, 360 cumec days) has not passed through the turbines. This results into less average power generation in the field (Table 4.5) by 66.2 MW while the same total irrigation requirements are met during the periods under operation optimization study.

   Pong last period ending storage contents are higher in the study 1 and 2 (94616 and 97639 cumec days) compared to field achieved (79457 cumec days). However, Bhakra last period ending storage contents are higher in study-1 (103790 cumec days) and lower in study 2 (83564 cumec days) compared to field achieved (95657 cumec days).

b) The affect of reduced irrigation requirements for study 1 and 2 have been analysed in Tables 4.8 and 4.9. The

Table 4.4 Bhakra-Beas System Operation Optimization Results for Study 1

Interval	Period	BHAKRA RESERVOIR					PONG RESERVOIR					Contribution from Ravi	Total irrigation releases
		Satluj Inflows (cumec)	Power discharge (cumec)	Spills (cumec)	Storage content (m^3)	Power generated (MW)	Beas Inflows (cumec)	Power discharge (cumec)	Spills (cumec)	Storage content (m^3)	Power generated (MW)	(Cumec)	(cumec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	September (21-30)	607.00	784.9	0	104152	836.2	430.51	360.0	124.4	101132	238.1	0.0	1271.3
2.	October	427.39	554.1	0	100202	585.2	180.74	328.2	0.0	96561	214.9	0.0	883.0
3.	November	301.27	535.0	0	93188	553.6	129.97	324.8	0.0	9715	208.1	0.0	860.0
4.	December	229.04	505.3	0	84625	507.5	124.65	305.0	0.0	85140	191.6	0.0	809.1
5.	January	203.74	437.0	0	77392	424.6	82.78	236.8	0.0	80388	145.6	0.0	673.1
6.	February	228.27	515.0	0	69072	482.5	168.61	314.3	0.0	76161	190.3	15.0	844.1
7.	March	307.37	439.2	0	64985	398.4	265.81	238.3	0.0	77015	143.2	29.2	706.7
8.	April	474.62	488.5	0	64569	437.5	219.80	287.6	0.0	74979	172.4	36.0	812.1
9.	May	433.65	624.0	0	58656	548.7	257.39	360.0	4.6	77035	212.9	195.1	1184.1
10.	June (1-10)	411.22	707.3	0	55695	604.5	164.99	360.0	74.3	68342	209.7	132.0	1273.9
11.	June (11-20)	814.14	765.6	0	56199	647.3	305.55	360.0	84.1	66955	207.6	132.0	1340.0
12.	June (21-30)	1829.29	719.7	0	67295	632.5	668.90	360.0	79.4	69250	208.1	132.0	1291.4
13.	July	1492.30	921.6	0	85001	874.3	873.71	299.9	0.0	87037	181.2	49.7	1271.3
14.	August	1215.90	635.3	0	103029	650.1	791.25	360.0	53.1	98760	230.7	26.0	1074.4
15.	September (1-10)	853.00	691.0	0	104653	733.0	315.55	360.0	84.5	97471	235.1	9.4	1144.9
16.	September (11-20)	591.50	678.1	0	103790	720.2	185.13	360.0	110.6	94616	233.4	0.0	1148.7

Table 4.5 Bhakra-Beas System Operation Optimization Results for Study 2

Interval	Period	BHAKRA RESERVOIR					PONG RESERVOIR					Contribution from Ravi (cumec)	Ropar Head works releases (cumec)	Harike Head works releases (cumec)	Total irrigation releases (cumec)
		Satluj Inflows (cumec)	Power discharges (cumec)	Spills (cumec)	Storage contents (m^3)	Power generated (MW)	Beas Inflows (cumec)	Power discharges (cumec)	Spills (cumec)	Storage contents (m^3)	Power generated (MW)				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1.	September (21-30)	607.00	809.2	0	103910	861.7	360.0	360.0	116.9	101226	238.1	0.00	757	529.2	1286.1
2.	October	427.39	659.8	0	96703	691.5	328.2	322.7	0.0	96825	211.4	0.00	656	326.5	982.0
3.	November	301.27	641.8	0	86486	651.3	324.8	318.1	0.0	91180	204.8	0.00	640	319.9	959.9
4.	December	229.04	645.3	0	74822	586.9	305.0	304.6	0.0	85603	192.0	0.00	500	409.9	909.9
5.	January	203.74	528.7	0	64749	486.4	236.8	227.8	0.0	81107	140.8	0.00	500	256.4	756.5
6.	February	228.27	565.0	0	54983	490.9	314.3	264.1	0.0	78336	160.9	15.31	550	294.5	844.5
7.	March	307.37	544.3	0	47639	444.9	238.3	243.3	0.0	79034	147.5	29.20	544	237.8	816.8
8.	April	474.62	591.0	0	44148	463.8	287.6	290.0	0.0	76926	175.3	36.00	500	417.1	917.1
9.	May	433.63	661.9	0	37069	494.2	360.0	321.0	0.0	74334	192.1	19.51	660	518.0	1178.0
10.	June (1-10)	411.22	768.3	0	33498	541.8	360.0	360.0	6.3	72320	213.2	132.20	750	517.0	1266.9
11.	June (11-20)	814.14	629.1	0	35348	439.2	360.0	314.7	0.0	72229	185.5	132.20	629	446.9	1075.9
12.	June (21-30)	1829.29	713.4	0	46570	533.3	360.0	360.0	1.7	75300	213.6	132.20	713	494.4	1207.4
13.	July	1492.30	804.9	0	67835	684.2	299.9	360.0	4.0	91108	222.2	49.70	740	478.7	1218.4
14.	August	1215.90	608.2	0	86730	579.9	360.0	360.0	143.0	10035	232.0	26.00	607	530.5	1137.5
15.	September (1-10)	853.90	846.0	0	86776	842.7	360.0	360.0	24.2	99349	236.4	9.42	746	493.8	1239.8
16.	September (11-20)	591.50	913.0	0	83564	903.2	360.0	356.1	0.0	97639	232.9	0.00	746	523.0	1269.0

Table 4.6 Bhakra-Beas System Operation Optimization Results for Study 3

Interval	Period	BHAKRA RESERVOIR					PONG RESERVOIR					Contribution from Ravi	Total irrigation releases
		Satluj Inflows (cumec)	Power discharges (cumec)	Spills (cumec)	Storage content (m^3)	Power generated (MW)	Beas Inflows (cumec)	Power discharge (cumec)	Spills (cumec)	Storage content (m^3)	Power generated (MW)	(cumec)	(cumec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	September (21-30)	612.57	739.9	0.0	94143	760.6	653.40	360.0	86.2	103987	239.0	0.0	1186.2
2.	October	368.23	517.4	0.0	89520	527.7	265.80	334.2	0.0	101865	221.9	0.0	851.6
3.	November	290.23	596.4	0.0	80335	589.3	96.09	356.4	0.0	94056	232.6	0.0	952.7
4.	December	228.88	541.8	0.0	70633	513.0	103.08	323.0	0.0	87234	205.5	0.0	864.9
5.	January	178.40	529.0	0.0	59760	474.6	90.08	308.0	0.0	80497	190.8	0.0	837.0
6.	February	195.61	557.5	0.0	49266	467.2	128.25	337.0	0.0	74444	203.3	15.0	909.8
7.	March	276.25	499.2	0.0	42355	391.2	190.51	286.4	0.0	71472	169.3	29.2	814.8
8.	April	294.45	589.0	0.0	33519	427.2	211.58	360.0	13.2	66622	209.0	36.0	998.2
9.	May	774.80	778.7	0.0	33399	537.3	258.78	360.0	33.1	53225	199.4	195.1	1666.0
10.	June (1-10)	1086.70	736.7	0.0	36899	518.7	265.66	360.0	242.0	49861	190.2	132.0	1470.9
11.	June (11-20)	939.90	693.4	0.0	39364	505.1	252.12	360.0	192.2	46861	186.4	132.0	1377.8
12.	June (21-30)	1711.00	742.0	0.0	49054	572.7	1140.48	360.0	264.1	52064	187.7	132.0	1498.4
13.	July	1690.00	773.9	0.0	76028	679.3	1894.59	360.0	414.6	86783	208.2	49.7	1598.2
14.	August	1976.00	980.0	219.20	100110	978.0	2168.88	360.0	1412.6	99066	230.7	26.0	2998.0
15.	September (1-10)	1346.60	774.9	0.0	105826	819.6	982.87	360.0	253.7	102758	237.4	9.4	1398.1
16.	September (11-20)	922.30	980.0	2.1	105228	1045.3	751.37	360.0	266.8	104004	239.4	0.0	1609.0

Table 4.7 Bhakra-Beas System Operation Optimization Results for Study 4

Interval	Period	BHAKRA RESERVOIR Satluj Inflows (cumec)	BHAKRA RESERVOIR Power discharges (cumec)	BHAKRA RESERVOIR Spills (cumec)	BHAKRA RESERVOIR Storage contents (m^3)	BHAKRA RESERVOIR Power generated (MW)	PONG RESERVOIR Beas Inflows (cumec)	PONG RESERVOIR Power discharges (cumec)	PONG RESERVOIR Spills (cumec)	PONG RESERVOIR Storage contents (m^3)	PONG RESERVOIR Power generated (MW)	Contribution from Ravi (cumec)	Total irrigation releases (cumec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	September (21-30)	361.81	750.8	0	96079	780.8	446.40	308.9	0.0	78941	186.9	0.0	1059.6
2.	October	241.34	535.6	0	86957	543.4	273.72	318.8	0.0	77544	192.9	0.0	854.4
3.	November	182.61	470.3	0	78327	460.2	154.95	208.0	0.0	75950	125.1	0.0	678.4
4.	December	138.10	490.9	0	67389	458.8	112.68	269.0	0.0	71104	159.5	0.0	759.9
5.	January	119.82	476.5	0	56334	419.0	145.55	226.5	0.0	68595	132.0	0.0	703.0
6.	February	106.31	623.5	0	41335	499.6	139.17	119.1	0.0	69178	69.1	15.0	758.0
7.	March	101.02	463.2	0	30109	327.1	123.64	186.5	0.0	67229	107.8	29.2	678.8
8.	April	118.39	432.4	0	20688	263.0	159.63	97.0	0.0	69109	56.1	36.0	565.3
9.	May	186.71	283.6	0	17696	152.0	278.27	99.1	0.0	74664	58.3	195.1	577.4
10.	June (1-10)	470.70	644.0	0	15963	324.4	310.30	102.7	0.0	76739	61.5	132.0	879.0
11.	June (11-20)	303.28	397.9	0	15016	192.2	223.47	102.3	0.0	77950	61.6	132.0	632.3
12.	June (21-30)	823.61	542.1	0	17832	269.4	731.71	323.4	0.0	82035	197.2	132.0	997.7
13.	July	795.00	741.5	0	19490	392.9	1798.24	360.0	729.8	103995	230.6	49.7	1881.0
14.	August	1357.62	980.0	113	27687	576.9	1684.77	360.0	1325.0	103986	239.9	26.0	2804.0
15.	September (1-10)	1008.00	795.6	0	29811	514.3	1086.00	360.0	832.3	102923	239.4	9.4	1997.0
16.	September (11-20)	1072.00	915.9	0	31371	608.3	1113.50	360.0	633.2	104126	239.5	0.0	1909.1

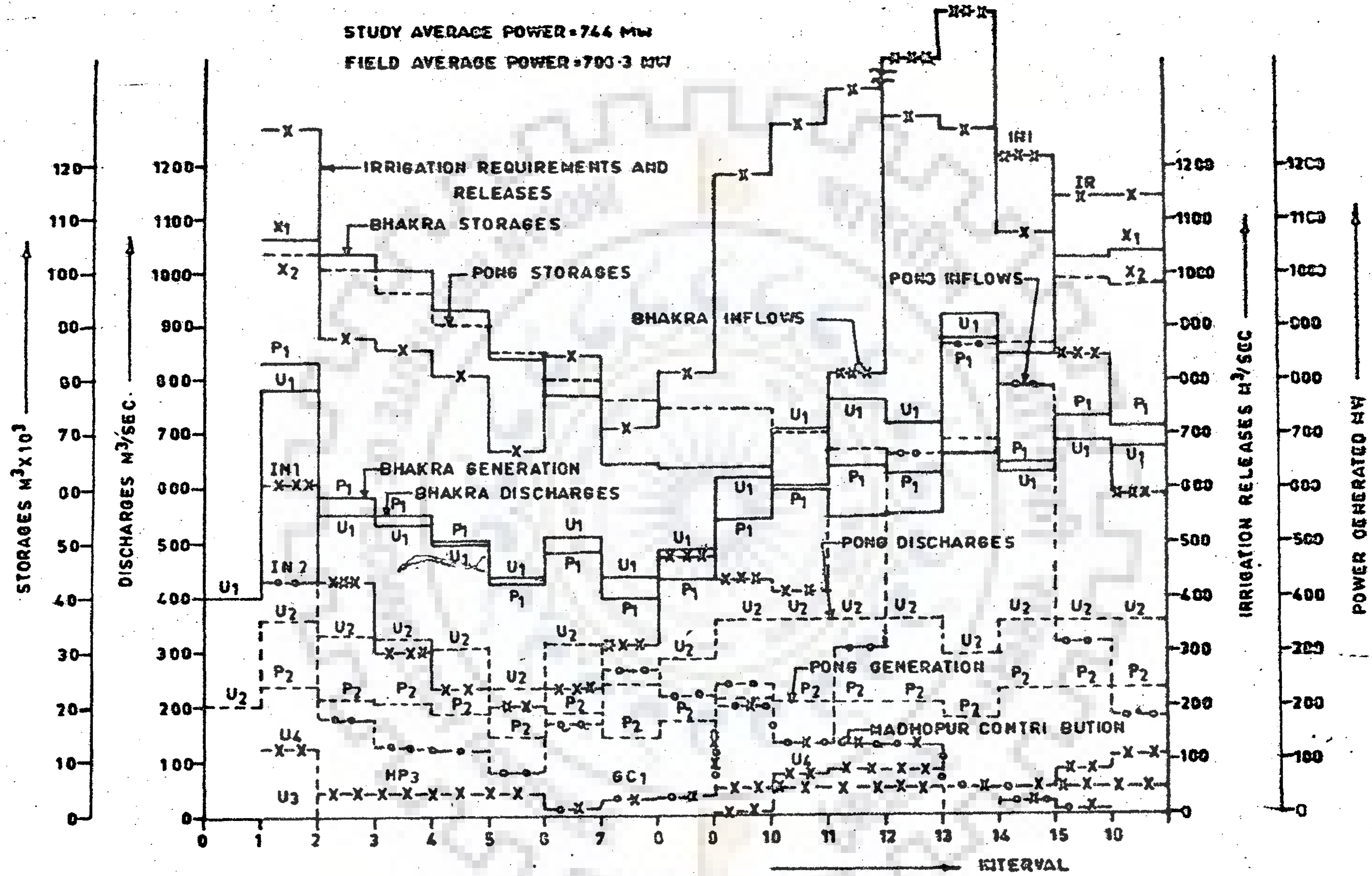


FIG. 4.7 BHAKRA-BEAS RESERVOIR SYSTEM OPTIMAL OPERATION STUDY 1

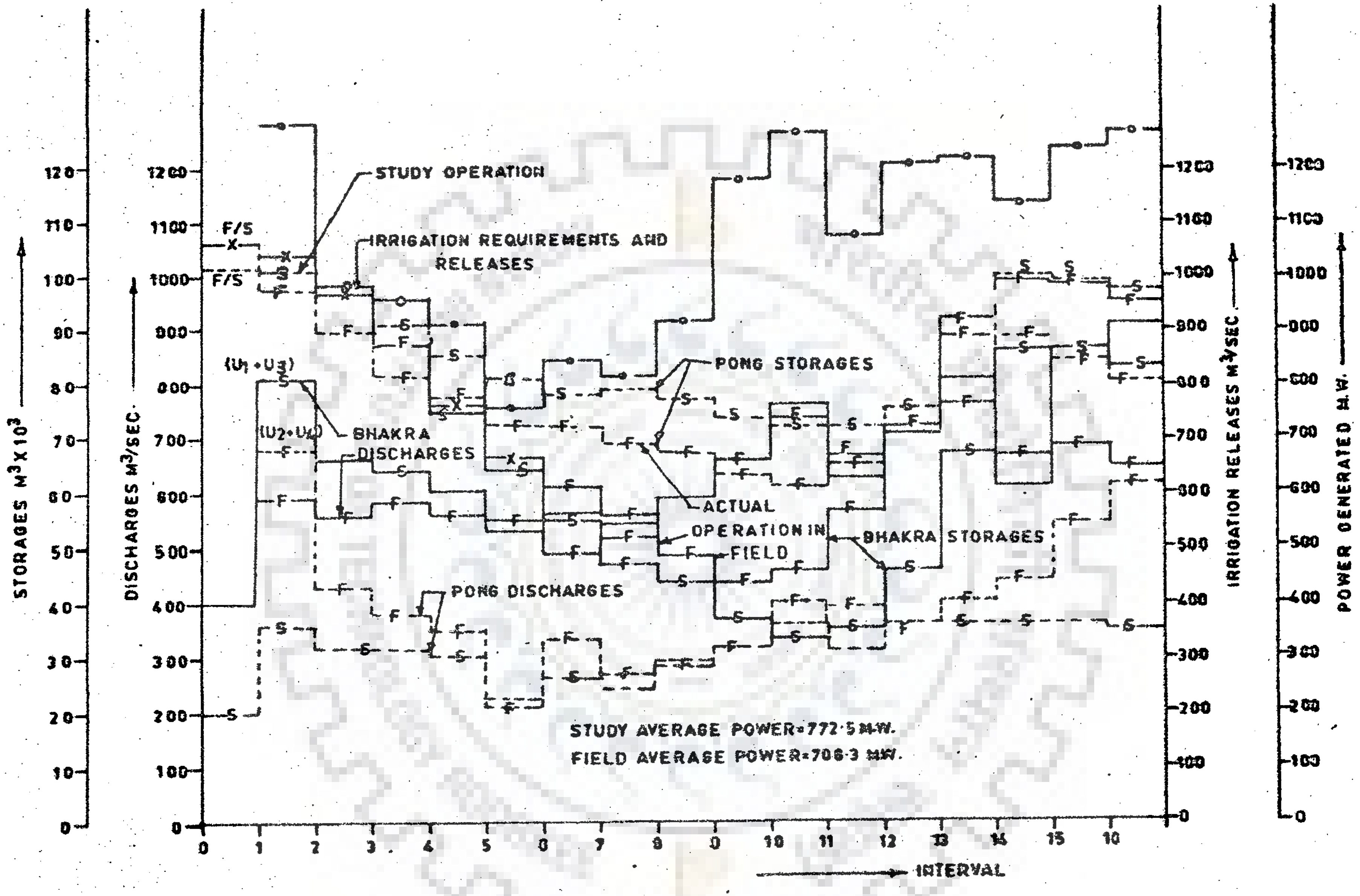


FIG.4·8 BHAKRA-BEAS RESERVOIR SYSTEM OPTIMAL OPERATION STUDY 2

Table 4.8 Comparison of Bhakra-Beas Reservoir System Operation Optimization Study 1,2 and 3 and Field Results

Sl. No.	Variables		Study - 1 (1979-80)					Study-2 (1979-80)					Study-3 (1978-79)				
			Bhakra Reservoir		Pong Reservoir		Total	Bhakra Reservoir		Pong Reservoir		Total	Bhakra Reservoir		Pong Reservoir		Total
1.	Total Inflows (cumec days)	Study	214548		115334		329882	214548		115334		329882	258247		207595		465842
		Field	214548		115334		329882	214548		115334		329882	258247		207595		465842
2.	Total out-flows (cumec days)	Study	215994		122444		338438	236970		119587		356557	257695		216495		474190
		Field	222799		134709		357508	222799		134709		357508	247884		214410		462294
3.	Difference Inflows-Out-flows (cumec days)	Study	- 1446		- 7110		- 8556	- 22422		- 4253		- 26675	9811		2088		11899
		Field	- 8251		- 19375		- 27626	- 8251		- 19375		- 27626	10166		- 17243		- 7077
			Initial	Final	Initial	Final		Initial	Final	Initial	Final		Initial	Final	Initial	Final	
4.	Storage content(m^3)	Study	105928	103790	101690	94616		105928	83564	101690	97639		95417	105228	101915	104004	
		Field	105928	95657	101690	79457		105928	95657	101690	79457		95417	105495	101915	104848	
5.	Total Average Power Generated (MW)	Study	-		-		744.0	-		-		772.5	-		-		793.1
		Field	-		-		706.3	-		-		706.3	-		-		788.0
6.	Additional Average Power Availability by optimization study (MW)		-		-		37.7	-		-		66.2	-		-		5.1

Table 4.9 Affect of Reducing Irrigation Requirements on Bhakra-Beas Reservoir Storages and Power Generation

		Trial Runs					
		(1)	(2)	(3)	(4)	(5)	(6)
1. Ending Storages (m^3)							
	Bhakra	89685	90314	90957	92740	92184	95380
	Pong	97608	97982	98339	99219	99671	103433
2. Average Power (MW)							
	Bhakra	564.7	563.1	561.3	557.5	558.2	549.7
	Pong	193.2	192.6	192.0	191.6	191.5	187.3
	Total	757.9	755.7	753.3	749.1	749.7	737.0
3. Difference between Inflow and Outflow (cumec days)							
	Bhakra	-16243	-15614	-14971	-13188	-13744	-10548
	Pong	- 4082	- 3708	- 3351	- 2471	- 2019	-1741

inflow and outflow difference in study 1 is brought down to -8556 cumec days from -27626 cumec days (field achieved). The average power generation is 744 MW still higher than field operation results of 706.3 MW.

c) Study 3 results also indicate increase in average power generation by 5.1 MW. Study 3 last period storage contents (Bhakra 105228 cumec days and Pong 104004 cumec days) are higher than initial storage contents (Bhakra 95417 cumec days and Pong 101915 cumec days) and very near to field achieved storage contents (Bhakra 105495 cumec days and Pong 104848 cumec days). The inflow outflow difference, Table 4.8 for study 3 (11899 cumec days) and field operation results (-7077 cumec days) is indicative of inconsistency in the data for this study and not optimal due to spills. Affect of Weighting Coefficients is considerable and optimal results are shown in Table 4.10 with $W_1 = 58.7$, $W_2 = 100$ and $W_3 = 300$.

d) In study 4 even after reducing irrigation targets and varying weighting coefficients results into lower ending storage content for Bhakra reservoir Tables 4.7 and 4.11. It is concluded that since Pong machines were commissioned after March, 1978 the data pertains to September 21, 1977 to March 31, 1978 did not reflect the actual operation conditions.

e) The study analysis indicates that staggering of depletion periods of these reservoirs would not optimize the system operation and meet constraints (Table 4.12) contradictory to Bhalla and Bansal Planning Study (8) table 3.6)

Table 4.10 Affect of Variation of Weighting Coefficients, Study 3

Variables	Trial Runs (1)	(2)	(3)	(4)	(5)	(6)
W_1	50.0	58.0	58.6	58.7	58.8	58.85
W_2	100.0	100.0	100.0	100 .0	100.0	100.00
W_3	300.0	300.0	300.0	300.0	300.0	300.00
Average Power (MW)	794.5	782.0	793.0	798.3	794.0	793.10
Bhakra Storage (m^3)	95350.0	104635.0	106833.0	106282.0	106928.0	105228.00
Pong Storage (m^3)	104022.0	103980.0	97899.0	98642.0	86984.0	104004.00

Table 4.11 Affect of Variation of Weighting Coefficients, Study 4

Variables	Trial Runs (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
W_1	35.0	48.0	49.0	49.0	50.0	52.0	57.0	58.7
W_2	100	100	100	80	100	100	100	100
W_3	250	300	275	275	200	300	275	250
Average Power (MW)	543.2	559.2	546.0	554.2	546.6	538.9	547.3	553.2
Bhakra Storage (m^3)	33216	31371	39781	19192	33543	41691	27197	320531
Pong Storage (m^3)	104093	104126	112381	104153	104100	104028	114083	104137

Table 4.12 Bhakra-Beas Reservoir System Optimization Staggering Results for Study 2

	Trial Runs							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1. Storage content at the end of period (m^3)								
Bhakra Reservoir	89490	89397	68749	62935	83564	66320	34077	51132
Pong Reservoir	99735	99915	101800	102055	97639	102072	101626	101932
2. Total Average Power (MW)	768.5	765.0	782.6	779.9	772.2	795.9	783.9	777.0
3. Inflow and Outflow difference(cumec days)								
Bhakra Reservoir	-297	-359	-1156	-1374	-468	-1073	-1522	-1704
Pong Reservoir	-262	-196	- 81	- 25	- 274	- 83	- 40	-51
			13th iteration Excessive spills			14th iteration Excessive spills		

f) Most of the water withdrawal from Bhakra reservoir would also improve the energy generation in downstream under construction power plant at Anandpur Sahib and water needs of corresponding canals system.

Hence, to optimize the power output and meeting irrigation requirements, releases should be made from Pong limited to generation capacity and balance be made from Bhakra which is also being uprated by additional 300 MW generating capacity. Scheduled releases from Bhakra Power Plants are further optimized in the study reported in Chapter V.

In case at the end of study the storage contents are lower due to lower inflow received and or due to more water released for increased requirements, irrigation water targets for the next year should be reduced and more emphasis laid on Pong releases limited to generation capacity.

Human judgement is essential for optimum power generation and meeting irrigation requirement since water and power requirement are fluctuating and are more than uncertain inflows and the stored water in Bhakra Beas reservoirs.

4.7 Conclusions

This optimization study would be a valuable supplement to operation planners of Bhakra Beas System or any other multi-reservoir system especially at the time of taking fortnightly or monthly decisions for water releases for irrigation and power generation. The findings of analysis would effect savings in water, increase in energy and peak capabilities, Change in operating procedure and reallocation of storages have been suggested by optimization study.

4.8 Suggestions

In managing Bhakra Beas System operations, it is felt after this study that decision makers and central regulating offices lack in getting complete information at shorter intervals. The practice of supplying water based on irrigation and power requirements at a fixed rate for 15-30 days period should be changed to a shorter period. It is suggested that effort should be made by Bhakra Beas Management Board to install Computer Control, run real time programmes and perform numerical calculations on real-time data obtained from the dispatcher, inter-face remote and other computer subsystem (Power plants, substations and load dispatch centres).

CHAPTER V

OPTIMUM SCHEDULING OF GENERATION IN BHAKRA DAM POWER STATIONS

5.1 Introduction

The system operator faces the problem of meeting the demand in most economical way to utilize a given volume of water to be released for multiple purposes as decided by medium range study. This problem is known as generation scheduling problem. Besides this the daily load pattern of the system exhibit large variations between peak and off peak hours and during different seasons of the year as shown in Figs.5.1 and 5.2. If sufficient generation is kept connected to line to meet peak demand, it is uneconomical to run all the generators during off peak hours. Therefore, it poses another problem of determining which generators should be taken off, when and how long they should be taken off. This problem is known as unit commitment problem. This type of the analysis presented in this Chapter has not been attempted so far especially applicable to a real complex system with the operational constraints.

5.2 Objective of Study

The objective of the study is to develop a method for solution of unit commitment and generation scheduling problem in two hydro power stations below a common dam (Bhakra) which

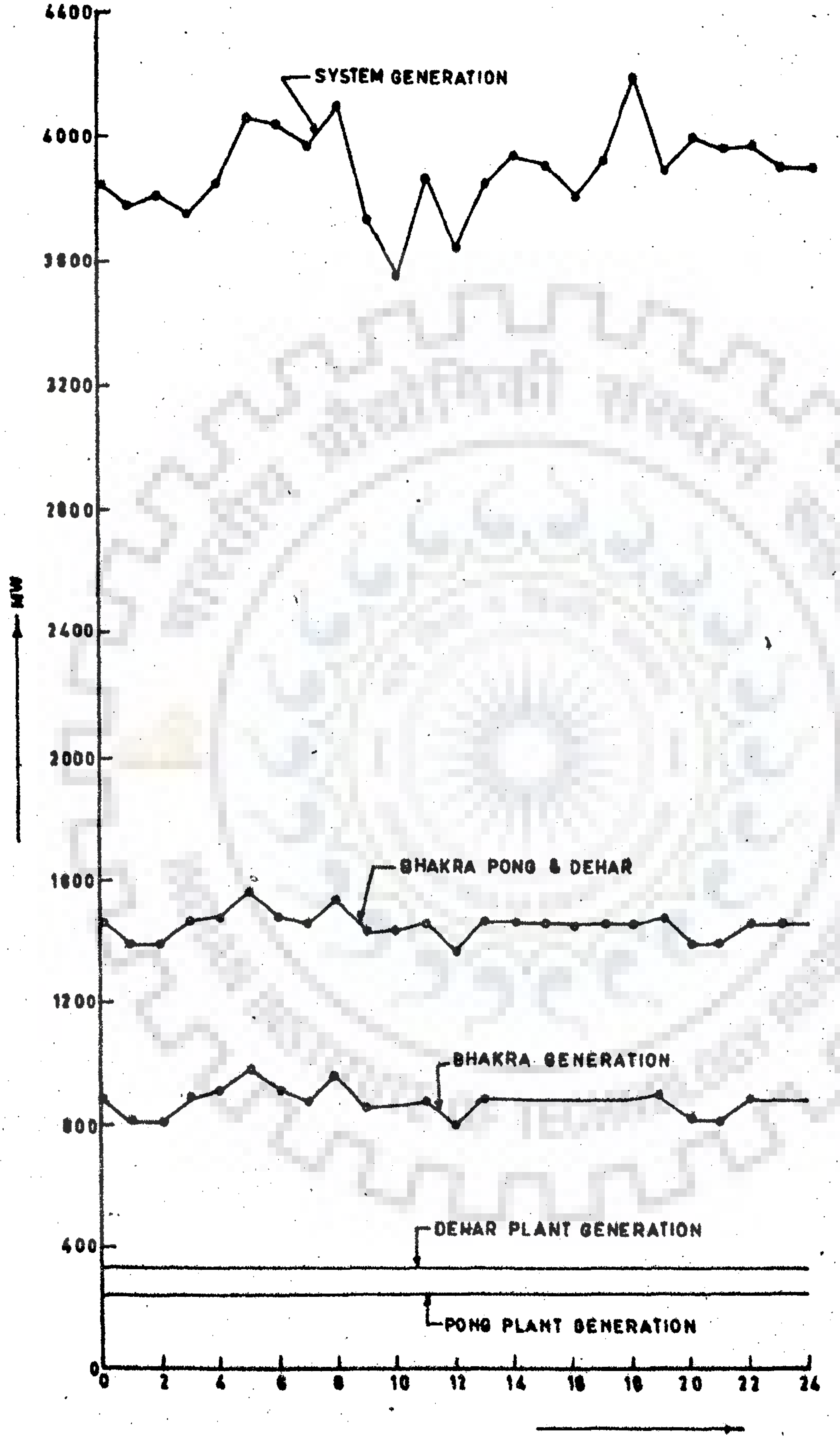


FIG. 5.1 TYPICAL DAY GENERATION CURVE FOR NORTHERN GRID WESTERN PART AND BHAKRA BEAS SYSTEM 27.8.79 (MONDAY)

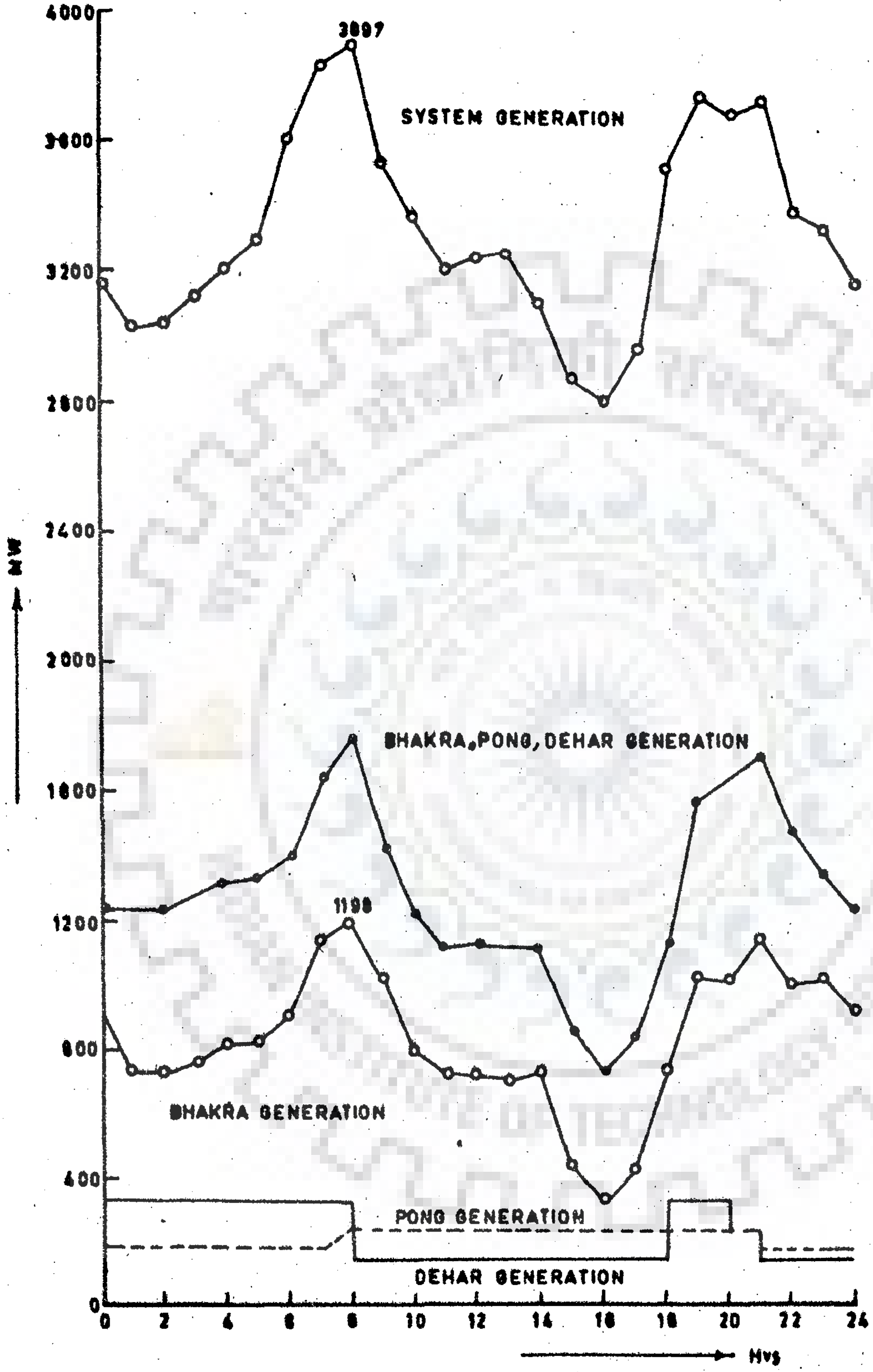


FIG. 5·2 TYPICAL DAY GENERATION CURVE FOR NORTHERN GRID WESTERN PART AND BHAKRA BEAS SYSTEM 1·11·79 (SATURDAY) gives the optimal releases through each turbine and the number of turbines to be run for meeting the demand. The hydro unit commitment depends on many factors such as head, discharge, storage and efficiency etc. In these power stations, the acting head on all units is same, therefore the minimum discharge is taken as objective function. A variety of operating constraints and spinning reserve requirements are considered. The problem is decomposed into two smaller subproblems - an integer programme and a nonlinear programming problem. The decomposition of the problem reduces computation time and storage.

5.3 System Description

There are two power plants at the dam known as Left Bank Power House and Right Bank Power House. In each plant 5 generators are installed of 90 MW and 120 MW (being uprated to 132 MW) capacity each respectively, at 400 ft. rated head. The function of the power plants **is** to supply power to Northern grid, maintain spinning reserve and perform frequency regulation function. Single line diagram of the plants and feeders are shown in Fig.5.3.

The monsoon and snowmelt water stored is released according to irrigation and power requirement, hence Dam reservoir head variation is large. It takes place between 512 ft.(155.06m) to 268 ft. (89.69m) throughout the year. The output of the Francis type turbines at minimum effective head and maximum

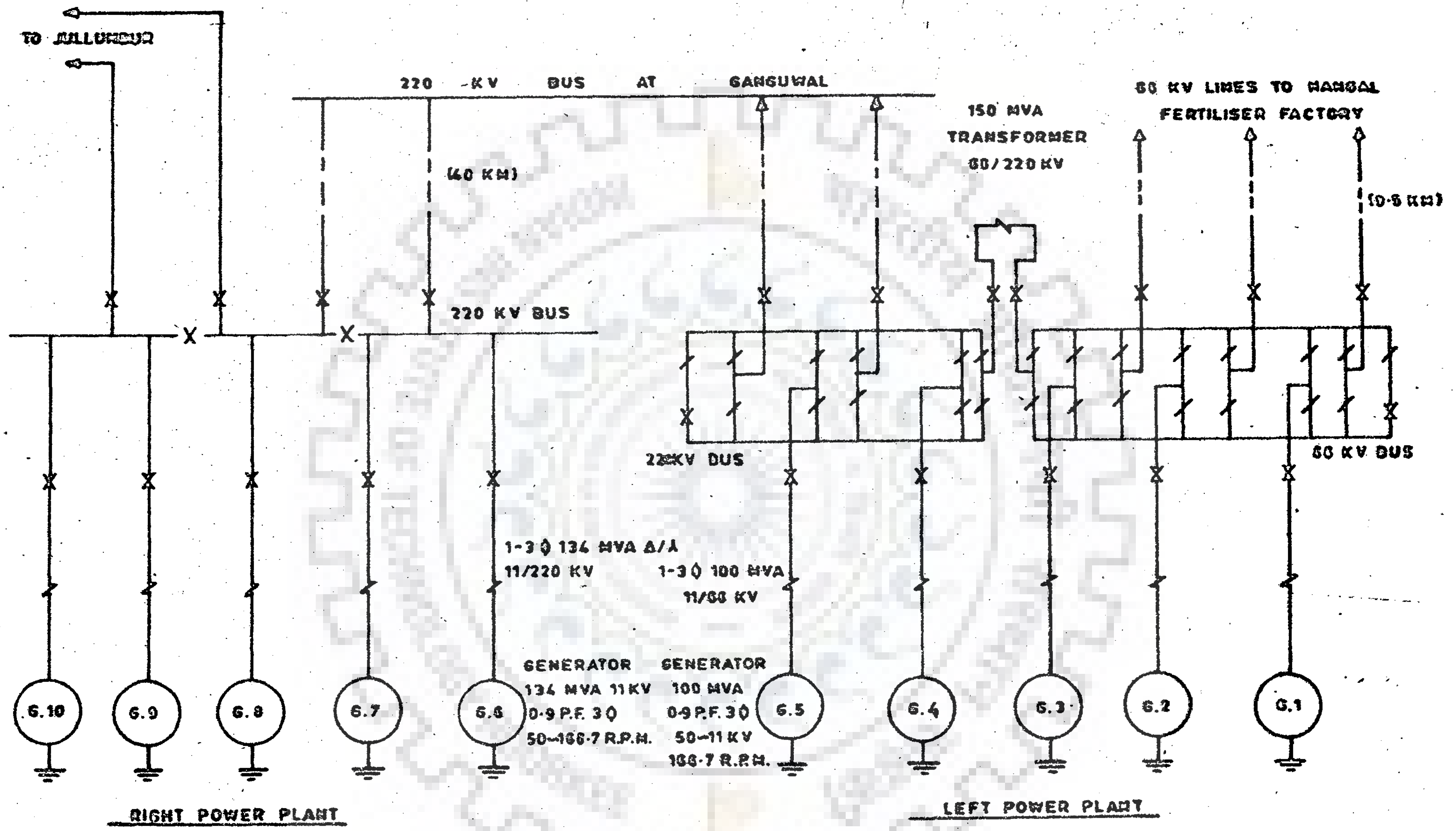


FIG 5·3. MAIN SINGLE LINE DIAGRAM OF HYDRO PLANTS (BHAKRA) effective head varies from 60-100 MW and 70-120 MW in Left and Right Power plants respectively. The efficiency of the machines vary with output and water head available. The discharge versus output in MW curves at different heads for the generators are shown in Figs.5.4 and 5.5 (supplied by BBMB).

The cavitation is excessive in a certain range of machine output as experienced by the operators and indicated by the suppliers. This phenomenon imposes restriction on the machine not to be operated in certain range. The safe operating zones have been given in Table 5.1 at different head conditions.

From Fig.5.3 it is evident that the interlinking transformer in Left Power Plant imposes 150 MVA transfer limit from 66 kV bus to 220 kV bus i.e. maximum surplus generation from units 1,2,3 which could be fed to the grid through this transformer. Similarly, to meet the auxiliary supply requirements unit No.1 or 2 or Unit No.3 in Left Power Plant and any unit out of 6,8 and 9 in Right Power Plant must run. In brief the following constraints were taken into account in this Generator scheduling study :

a) spinning reserve at the generating station,

b) efficiency of machines at the available head,

c) safe zone operation,

d) minimum and maximum machine capability,

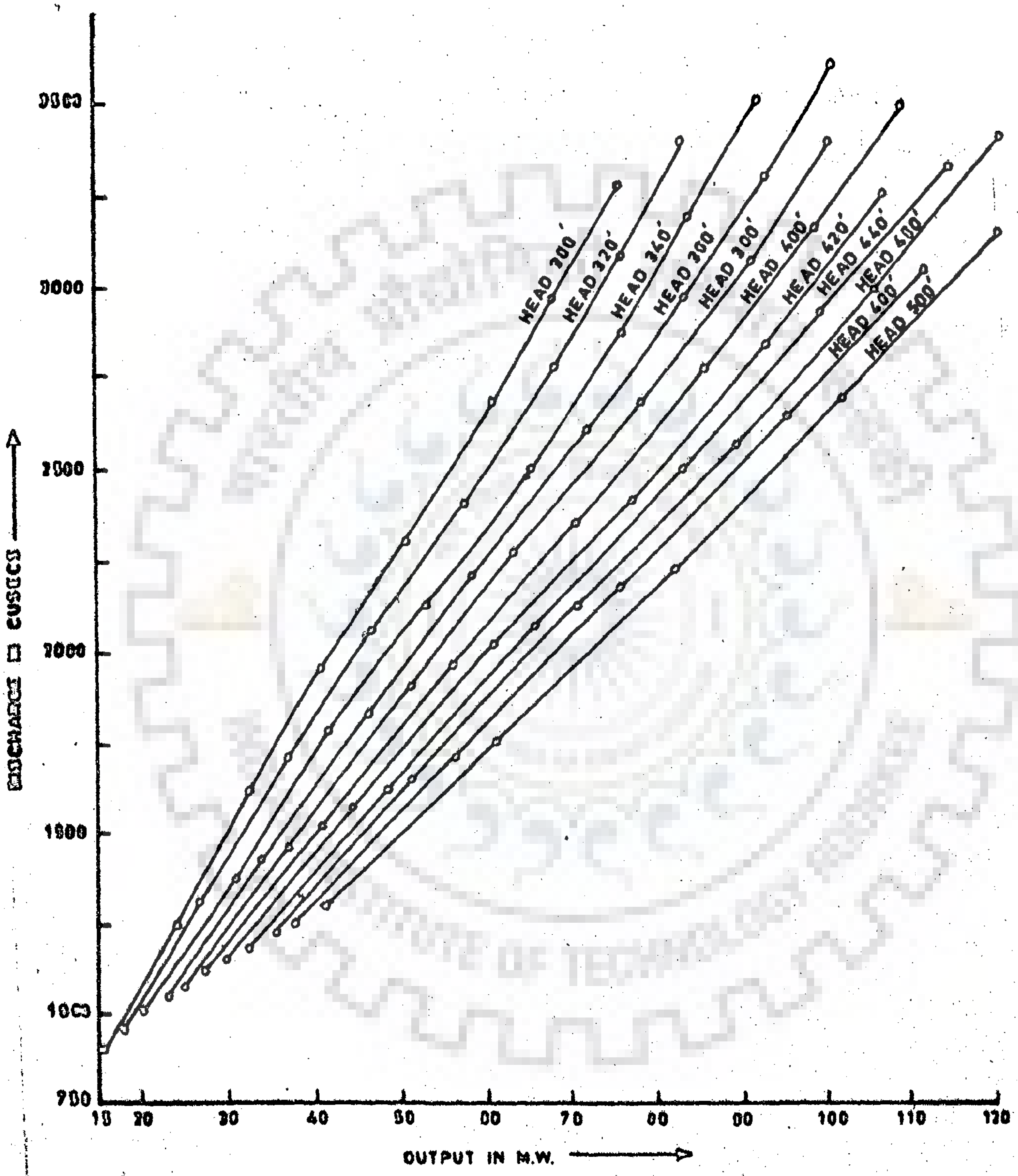


FIG 5·4 GENERATOR OUTPUT DISCHARGE CURVES BHAKRA LEFT PLANT

Table 5.1 Safe Operating Zones

Head Meter(ft)	Left Power Plant (Machine 1-5)	Right Power Plant (Machine 6-10)
89M(292 ft)	35-60 MW	60-85 MW
91.44M (300 ft)	35-65 MW	65-90 MW
97.53 M(320 ft)	40-75 MW	70-96 MW
103.652M(340 ft)	50-85 MW	70-105 MW
109.728M(360 ft)	65-90 MW	75-110 MW
115.82M(380 ft)	65-100 MW	80-120 MW
121.92M (400 ft)	70-100 MW	85-120 MW
128.016 M(420 ft)	70-100 MW	90-120 MW
134.112 M(440 ft)	80-100 MW	95-120 MW
140.208 M(460 ft)	90-100 MW	100-120 MW
146.30 M(430 ft)	90-100 MW	100-120 MW
155.667 M(500 ft)	90-100 MW	100-120 MW

Source : BBMB

e) interlinking transformer loading limit,

f) auxiliary supply constraint,

g) minimum discharge to maintain minimum tailwater level and

h) reservoir levels.

5.4 Curve Fitting of Power Plant Machine Performance Curves

The generating unit performance curves are given in Fig.5.4 and 5.5. These curves are drawn for various heads. Here these curves are approximated for the computer programme by a polynominal expression to obtain accuracies with in 0.5 MW. The shape of the power plant machine performance is approximated by the following polynomial :

$$P_G = Ak \ Q^B \tag{5.1}$$

where,

P_G	Machine generation
Ak and B	Performance curve constants
Q	Machine discharge

The method used is based on least squares criterion. The polynomial above represents the curves which are almost linear especially in the safe zone operation portion. The points (Mw and Q-discharge) for the study obtained from performance curves are tabulated in Appendix- V for Left and Right Power Plants and are taken from the straight line safe zone portion and more or less satisfy the polynomial. If the plotted points are N in number the sum of squares of the

N differences S^2 should be minimum.

Taking natural logarithm of equation 5.1

$$\text{Log}\, P_{G_i} = \text{Log}\, Ak + B\, \text{Log}\, Q_i$$

$$i = 1, \ldots\ldots, N \qquad (5.2)$$

This can be written as

$$Y_i = A + BX_i \qquad (5.3)$$

Where,

$\text{Log}\, P_{G_i} = Y_i$

$\text{Log}\, Ak = A$

$\text{Log}\, Q_i = X_i$

Therefore,

$$S^2 = \sum_{i=1}^{N} (A+BX_i-Y_i)^2 \qquad (5.4)$$

For minima the differential of S^2 should be zero :

$$\frac{\partial s^2}{\partial A} = 0 = 2 \sum_{i=1}^{N} (A+BX_i-Y_i) \qquad (5.5)$$

$$\frac{\partial s^2}{\partial B} = 0 = 2 \sum_{i=1}^{N} (A+BX_i-Y_i) \sum_{i=1}^{N} X_i \qquad (5.6)$$

Multiplying (5.5) by ΣX_i, (5.6) by N and subtracting (5.6) from (5.5).

$$NA\, \Sigma X_i + B\Sigma X_i^2 = \Sigma X_i\ \Sigma Y_i \qquad (5.7)$$

$$NA\, \Sigma X_i + NB\, \Sigma X_i^2 = N\Sigma X_i Y_i \qquad (5.8)$$

$$B\left[(\Sigma X_i)^2 - N\Sigma X_i^2\right] = \Sigma X_i \; \Sigma Y_i - N\Sigma X_i \; Y_i$$

$$B = \frac{\Sigma X_i \Sigma Y_i - N\Sigma X_i \; Y_i}{(\Sigma X_i)^2 - N\,\Sigma X_i^2} \tag{5.9}$$

and

$$A = \frac{\Sigma Y_i - B\Sigma X_i}{N} \tag{5.10}$$

Therefore,

$$Ak = \text{Exp}\left(\frac{\Sigma Y_i - B\Sigma X_i}{N}\right) \tag{5.11}$$

A computer sub programme for this method was prepared and given in Fig.5.6.

However, one more computer programme algorithm and flow chart based on the linearization by Taylor's Series of the above polynomial expression are given in Appendix 1 and Appendix II and were used after a few trial runs.

5.5 Mathematical Formulation of Problem

The scheduling period considered is 24 hours as the problem is basically repeated each day. This period is divided into number of one hour periods. The planning period begins with the system base load. The following factors are to be considered while formulating the problem(15,12) :

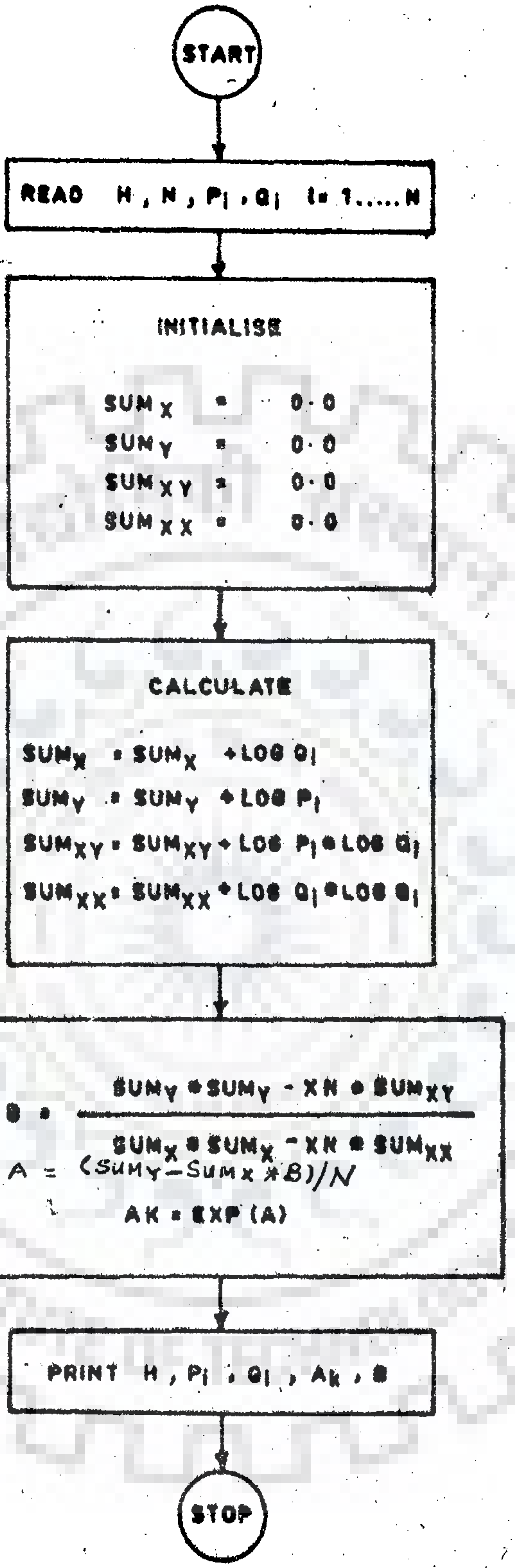


FIG. 5·6 FLOW CHART FOR LEAST SQUARE CURVE FITTING.

i) each unit is designed such that when it is committed to operation the unit output must be between its minimum and maximum operating capacities,

ii) the output of generators should be such that the demand is satisfied,

iii) planner requires reserve operating capacity not only to take into account the load fluctuations being frequency regulation plant but also to protect system against reduction in energy generation and also against the inability to satisfy demand when generation equipment failure occurs,

iv) some units should be kept on for auxiliary power supply in each plant,

v) total discharge from the power plants should be sufficient to maintain a specified tailrace level, and

vi) power transfer through interlinking transformer should not exceed its rating.

5.6 Mathematical Model

T represents the total number of intervals in which the scheduling period is divided and there are N (=10) generating units in the system. The binary variables X_{it} are used to denote the state of unit i in operation planning period t. That is, if $X_{it} = 1$, the i^{th} unit is operating in period t and $X_{it} = 0$, otherwise. The continuous variables Q_{it} represent the amount of water discharge from i^{th} unit in t^{th} time period.

The objective is to minimize the total discharge in each operation planning period. Mathematically it can be written as :

Minimize :

$$\sum_{i=1}^{N} \sum_{t=1}^{T} Q_{it} \tag{5.12}$$

The above function should be minimised such that the following inequality and equality constraints arising from system operating limits and design considerations discussed in Section 5.3 are satisfied.

(a) Demand Constraint : If $P_{G_{it}}$ is the output of i^{th} generating unit and PD_t is the demand (including auxiliary supply requirement) in t^{th} time period, then total generation should be equal to demand in each time period i.e.

$$\sum_{i=1}^{N} P_{G_{it}} = PD_t \tag{5.13}$$

where,

$P_{G_{it}}$ is expressed in terms of turbine discharge by the following relation :

$$P_{G_{it}} = Ak_i \quad Q_{it}^{B_i} \qquad i=1,\ldots,N$$

Ak_i and B_i are constant

(b) Capacity Constraint : The power output of any generating unit in each time period t should not exceed its rating $\overline{P}_{G_i}$ nor should it be below that is necessary for avoiding cavitation effect in turbine i.e. $\underline{P}_{G_i}$. In some cases maximum power output from a generating unit is also limited by penstocks flowing full, generation saturation or temperature rise on turbine running rough. Mathematically it can be written as :

$$\underline{P}_{G_i} X_{it} \leq P_{G_{it}} \leq \overline{P}_{G_i} X_{it} \qquad (5.14)$$

$$i = 1 \ldots\ldots N$$

$$t = 1 \ldots\ldots T$$

(c) Reserve Constraint : If R_t is the requirement for meeting load and spinning reserve in t^{th} time period then

$$\sum_{i=1}^{N} \overline{P}_{G_i} X_{it} \geq R_t \qquad (5.15)$$

(d) Auxiliary Power Supply Constraint : Auxiliary power supply can be met if any one unit out of units 1,2 and 3 on left bank as well as one unit out of units 6,8 and 9 on right bank are kept on in each time period t i.e.

$$X_{1t} + X_{2t} + X_{3t} \geq 1 \qquad (5.16)$$

$$X_{6t} + X_{8t} + X_{9t} \geq 1$$

(e) Tail Race Level Constraint : If Q_L is the minimum discharge required for maintaining the minimum tail race level then

$$\sum_{i=1}^{N} Q_{it} \geq Q_L \qquad (5.17)$$

Generation for minimum discharge of 4200 cusec to maintain minimum tail race level of 1166.5 feet at different heads are given in Table 5.2.

(f) Transformer Loading Constraints : If P_t^{NF} is the load of the Nangal fertilizer factory and auxiliary power requirement in t^{th} time period and P_T is the capacity of interlinking transformer then :

$$\sum_{i=1}^{3} P_{G_{it}} - P_t^{NF} \leq P_T \qquad (5.18)$$

$$\sum_{i=1}^{3} P_{G_{it}} \geq P_t^{NF} \qquad (5.19)$$

The complete optimization problem can be given by (5.12-5.19). The variables corresponding to a time period are independent of other time periods. Therefore, the problem can be decomposed interval wise. For t^{th} interval the problem can be written as :

Table 5.2 Minimum Tail Race Level Discharge

Discharge (cusecs) required to maintain minimum tail race level of 1166.5 ft. is 4200 cusecs.

Sl. No.	Head(ft)	Cusecs/MW	Generation for discharge of 4200 cusecs to maintain tail race level of 1166.5 ft MW
1	280	46.6	90
2	290	45.6	92
3	300	44.2	95
4	320	42.0	100
5	340	38.2	110
6	360	36.5	115
7	380	35.0	120
8	400	33.5	125
9	420	32.3	130
10	440	31.0	135
11	460	30.0	140
12	480	29.0	145
13	500	27.0	155

Source : BBMB

Minimize

$$\sum_{i=1}^{N} Q_{it} \tag{5.20}$$

Subject to the constraints :

$$\sum_{i=1}^{N} P_{G_{it}} = PD_t \tag{5.21}$$

$$\underline{P}_{G_i} X_{it} \le P_{G_{it}} \le \overline{P}_{G_i} X_{it} \tag{5.22}$$

$i = 1.....N$

$$\sum_{i=1}^{N} \overline{P}_{G_i} X_{it} \ge R_t \tag{5.23}$$

$$X_{1t} + X_{2t} + X_{3t} \ge 1 \tag{5.24}$$

$$X_{6t} + X_{8t} + X_{9t} \ge 1 \tag{5.25}$$

$$\sum_{i=1}^{N} Q_{it} \ge Q_L \tag{5.26}$$

$$\sum_{i=1}^{3} P_{G_{it}} \ge P_t^{NF} \text{ , and} \tag{5.27}$$

$$- P_t^{NF} + \sum_{i=1}^{3} P_{G_{it}} \le P_T \tag{5.28}$$

5.7 Solution Technique

The optimization problem given by (5.20-5.28) is a mixed integer nonlinear programming problem which is a complex one. This problem is decomposed into two subproblems an integer programme containing only binary variables X_{it} and a nonlinear programming problem containing only continuous variables Q_{it}.

5.7.1 Integer programming problem

The integer programming problem for t^{th} time period is :

$$\text{Minimize } Z(X) = \sum_{i=1}^{N} a_i X_{it} \tag{5.29}$$

Where,

$$a_i = \frac{1}{Ak_i \; B_i} \tag{5.30}$$

Subject to constraints :

$$\sum_{i=1}^{N} \overline{P}_{G_i} \; X_{it} \geq R_t \tag{5.31}$$

$$X_{1t} + X_{2t} + X_{3t} \geq 1 \tag{5.32}$$

$$X_{6t} + X_{8t} + X_{9t} \geq 1 \tag{5.33}$$

$$\sum_{1}^{3} \overline{P}_{G_i} \geq P_t^{NF}, \text{ and} \tag{5.34}$$

$$-P_T + \sum_{i=1}^{3} P_{G_i} X_{it} - P_t^{NF} \leq 0 \tag{5.35}$$

5.7.2 Nonlinear programming problem

The nonlinear programming problem can be written as :

$$\text{Minimize } \sum_{i_t X^*} Q_{it} \tag{5.36}$$

Subject to constraints :

$$\sum_{i \in X} PG_{it} = PD_t \text{ , and} \tag{5.37}$$

$$\underline{P}_{G_i} \leq P_{G_{it}} \leq \overline{P}_{G_i} \quad i \in X^* \tag{5.38}$$

Where, X is set of units which are on. This set is obtained by solving integer programming problem.

5.7.3 Stepwise procedure for mixed integer nonlinear programming problem

The stepwise procedure for the mixed integer nonlinear programming problem (5.29-5.38) is :

1. Set t = 1
2. Solve corresponding integer programming problem (5.29-5.35)
3. Solve nonlinear programming problem(5.36-5.38)
4. Set t = t+1. If $t \geq T$ stop, otherwise go to next step.

5.7.4 Method for solving integer programming problem

The basic steps of the method for solving integer programming problem (87) are :

1. Set $\hat{X} = X = (0,0.....0)$ and $Z(\hat{X}) = \infty$
2. If $Z(X) \leq Z(\hat{X})$, skip to X^* and repeat. Otherwise go to next step.
3. If for any i = 1,2,6, $g_i(X^* - 1) > 0$ skip to X^* and go to step 2.

4. If for all $i = 1,2,\ldots\ldots,6$ $g_i(X) \geq 0$, set $\hat{X} = X$ and store $Z(\hat{X})$. Skip to X^* and go to step 2. Otherwise change X to X+1 and go to step 2.

If X is the current vector, then the next vector is denoted by X+1. The vector X^* is calculated from vector X as follows :

a) substract logically one from X to obtain X-1.

b) perform logically or operation on X and X-1 to obtain X^*-1.

c) add logically 1 to X^*-1 to obtain X^*

Flow chart for this technique is shown in Fig.5.7 and computer subprogramme forms subroutine of the main programme.

5.7.5 Method for solving nonlinear programming problem

The constrained nonlinear programming problem (5.36 to 5.38) is reformulated by using Lagrangian multiplier as :

Minimize

$$Z = \sum_{i \varepsilon X^*} Q_{it} + \lambda \quad (PD_t - \sum_{i \varepsilon X^*} P_{G_{it}}) \qquad (5.39)$$

Subject to inequality constraint given by dropping the inequality constraints and by applying the optimality conditions we have,

$$\frac{\partial Z}{\partial Q_i} = 0$$

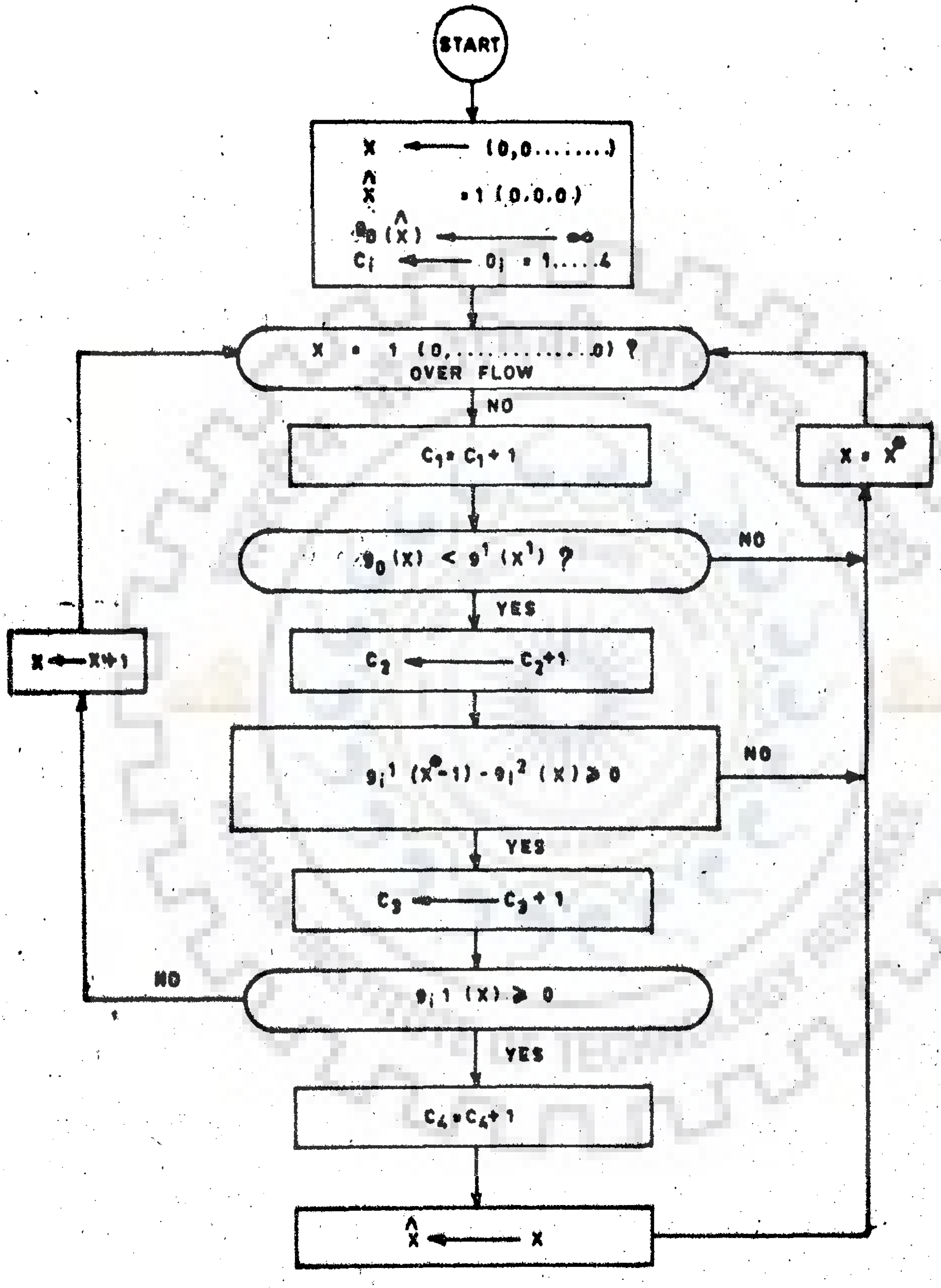


FIG 5·7 FLOW CHART OF INTEGER PROGRAMME

$$\text{i.e.} \quad 1 + \lambda \left[\Sigma \frac{\partial P_{G_{it}}}{\partial Q_{it}} \right] = 0$$

$$\text{or} \quad 1 + \lambda \left[- \Sigma Ak_i B_i \; Q_{it}^{B_{i-1}} \right] = 0 \qquad (5.40)$$

From above expression

$$Q^{*}_{it} = \left[\frac{1}{\lambda \; Ak_i B_i} \right] 1/ (B_{i-1}) \qquad (5.41)$$

$$P^{*}_{G_{it}} = Ak_i \; \overset{*}{Q}_{it}^{B_i} \; , \; i \epsilon X^{*} \qquad (5.42)$$

Therefore, the basic steps of the method (50,68) are :

1) Choose initial value of λ. Set $S = X^{*}$

2) Calculate $P^{*}_{G_{it}}$ $(i \epsilon S)$ with the help of (5.41 and 5.42)

3) Check if $P^{*}_{G_{it}} \geq \overline{P}_{G_i}$, set $P^{*}_{G_{it}} = \overline{P}_{G_i}$ or if $P^{*}_{G_{it}} < \underline{P}_{G_i}$

set $P^{*}_{G_{it}} = \underline{P}_{G_i}$, Remove this unit from set S and go to step 2. Otherwise, go to step 4.

4) Calculate P_L

$$P_L = \sum_{i \epsilon X^{*}} P_{G_i} - PD_t$$

5) If $| P_L | \leq$ tolerance, then solution is obtained, otherwise go to next step.

6) Modify value of λ

$$\lambda = \lambda + \alpha \; P_L$$

where $\alpha > 0$ is a constant. Go to step 2.

The above method is simulated on the digital computer forming as main programme and flowchart is given in Fig.5.8.

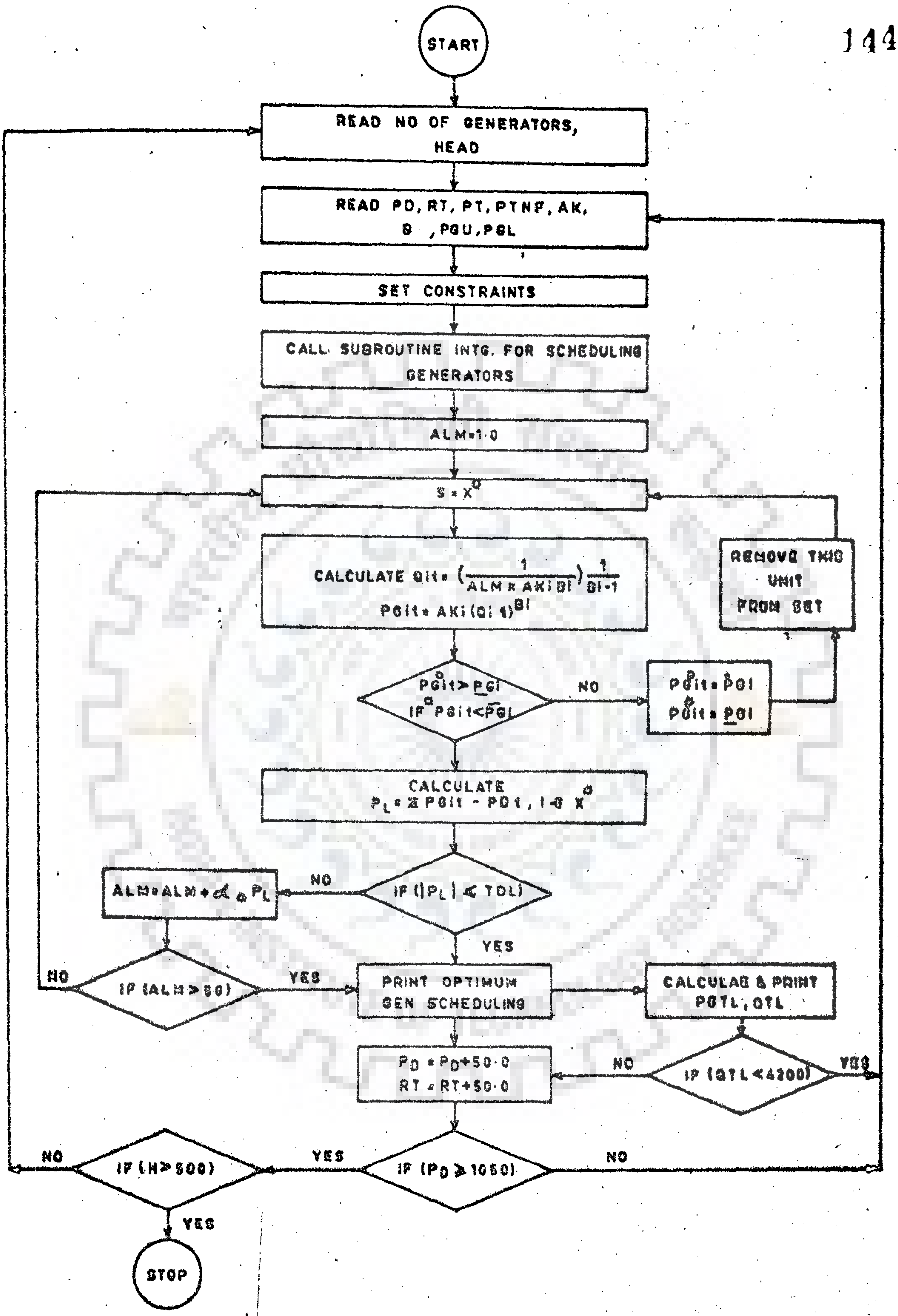


FIG. 5·8 FLOW CHART OF GENERATION SCHEDULING NON LINEAR PROGRAMME

5.8 Results and Analysis

(a) Generation scheduling calculations by hand (as being done actually in the field) and results obtained through this optimization study are listed in Table 5.3. For the computer studies the following data was considered as constraint.

PD = Varied from 300 to 1050 MW

Spinning Reserve = Varied from 25 - 120 MW

P_t^{NF} = 145 MW

PT = 120 MW

H = Varied from 300'-500' in 20 ft. steps.

Minimum discharge constraint = 4200 cusecs.

(b) It is observed from Table 5.3 that as the spinning reserve increases the number of machines to be scheduled may increase. Hence the optimal generation position on the performance curve shifts to a lower generation point causing more water to draw keeping minimum and maximum generation constraints within limits. This appears to be responsible for getting higher discharges in optimized results as compared to hand calculation in some cases. For example, in hand trial calculations the machines have been scheduled at any load condition at their maximum generation points. Spinning reserve in most of the cases is maximum capacity of machines minus the load, whereas optimization results consider spinning reserve as a constraint first which must be met and added in the load for scheduling the machines.

Table 5.3 Optimum Generation Scheduling Results of Bhakra Power Plants

Head (Ft)	Load demand on Bhakra Power Plants (MW)	Hand Calculations: Scheduling of machines: Left Bank	Hand Calculations: Scheduling of machines: Right Bank	Hand Calculations: Total Generation(MW)	Hand Calculations: No. of machines	Hand Calculations: Spinning Reserve (MW)	Hand Calculations: Total discharges (cusecs)	Optimization Study Results: Totaldischarges (cusecs)	Optimization Study Results: Spinning Reserve (MW)
1	2	3	4	5	6	7	8	9	10
268	200	1x47 2x44	65x1	200	4	31	9980		
	250	1x46 2x42	2x60	250	5	53	12520		
	300	2x53 1x52	2x71	300	5	3	14450		
	350	2x47 1x46	3x70	350	6	25	16860		
	400	2x47 1x46	4x65	400	7	47	19560		
	450	3x47 1x49	4x65	450	8	50	21010		
	500	4x47 1x52	4x65	500	9	53	24470		
	550	5x47	5x63	550	10	75	27150		
	600	5x51	5x69	600	10	25	28950		

Table 5.3 (Contd.)

1	2	3	4	5	6	7	8	9	10
320	200	60x2	80x1	200	3	58	8362.50		
	250	75x2	95x1	245	3	13	10087.50		
	300	70x3	90x1	300	4	38	12351.00	12565	40
	350	65x4	90x1	350	5	68	14463.50	14568	45
	400	75x4	95x1	395	5	23	16212.50	16664	35
	450	72x5	90x1	450	6	48	18294.50	18672	40
	500	75x4	95x2	490	6	26	20175.00	20782	30
	550	70x4	90x3	550	7	64(35)	22900.00	22778^{++}	35
	600	70x1 65x4	90x3	600	8	94	24662.50	24876	25
	650	75x5	92x3	651	8	43	26637.50	26873	30
	700	72x5	85x4	700	9	92(55)	29175.00	29029^{++}	55
	750	74x5	95x4	750	9	42	31162.50	30976^{+}	25
	800	70x5	90x5	800	10	90	32823.75	33154^{+}	0
	850	75x5	95x5	850	10	40	35125.00		
360	200	90x1	110x1	200	2	10	7225.10		
	250	80x2	90x1	250	3	50	9400.00		
	300	90x2	112x1	292	3	8	10450.00	11109	82
	350	85x2	90x2	350	4	70(54)	13050.00	12863^{++}	54
	400	90x2	110x2	400	4	20	14450.00	14669	72
	450	85x3	98x1 97x1	450	5	60	16525.00	16514^{++}	60

Table 5.3(Contd.)

1	2	3	4	5	6	7	8	9	10
	500	90x3	112x2	494	5	16	17675.00	18349	84
	550	85x4	105x2	550	6	50	19740.00	20059	56
	600	90x3	110x3	600	6	30	21675.00	22025	96
	650	85x3 80x1	105x3	650	7	70	23455.00	23716	68
	700	90x4	112x3	696	7	24	24900.00	25690	108
	750	65x4	101x1 103x3	750	8	90	27085.00	27265	58
	800	90x4	110x4	800	8	40	28900.00	29345	120
	850	85x5	106x3 107x1	850	9	80	30580.00	30917	70
	900	90x5	112x4	898	9	32	32125.00		
	950	85x5	105x5	950	10	100	35062.50		
	1000	90x5	110x5	1000	10	50	36150.00		
400	200	85x1	115x1	200	2	10	6550.00		
	250	75x2	100x1	250	3	50	8320.00		
	300	90x2	120x1	300	3	Nil	9750.00	10097	90
	350	90x1 75x2	110x1	350	4	40	11540.00	11692	70
	400	90x2	110x2	400	4	20	13125.00	13275	80
	450	83x3	101x2	450	5	40	14687.50	14866	60
	500	90x3	115x2	500	5	10	16320.00	16696	100

Table 5.3(Contd.)

1	2	3	4	5	6	7	8	9	10
	550	85x3 75x1	110x2	550	6	50	18100.00	18031^{++}	50
	600	90x4	120x2	600	6	Nil	19500.00	19783	60
	650	85x4	103x2 104x1	650	7	70	21440.00	21374^{++}	70
	700	90x4	113,33x3	700	7	21	22820.00	22952	50
	750	90x3	20x4	750	7	Nil	24737.50	24742^{+}	90
	800	90x4	110x4	800	8	40	26250.00	26316	70
	850	90x3	116x5	850	8	20	27737.50	28048	110
	900	84x5	120x4	900	9	30	29600.00	29426	62
	950	90x4	118x5	950	9	10	31212.50		
	1000	85x5	115x5	1000	10	50	32800.00		
	1035	90x4 75x1	120x5	1035	10	Nil	34187.50		
440	200	85x1	115x1	200	2	10	6050.00		
	250	77x2	96x1	250	3	50	7680.00		
	300	90x2	120x1	300	3	Nil	9025.00	9323	90
	350	80x3	110x1	350	4	40	10635.00	10806	70
	400	90x2	110x2	400	4	20	12125.00	12285	80
	450	82.5x4	120x1	450	5	30	13875.00	13768^{+}	90
	500	90x3	115x2	500	5	10	15350.00	16384^{+}	130
	550	82.5x4	110x2	550	6	50	16620.00	16712	50

Table 5.3(Contd.)

1	2	3	4	5	6	7	8	9	10
	600	90x4	120x2	600	6	Nil	18050.00	18329	60
	650	85x4	113.3x3	650	7	70	19795.00	19809^{++}	
	700	90x4	113.3x3	700	7	20	21300.00	21272^{+}	50
	750	90x3	120x4	750	7	Nil	22600.00	22886	90
	800	90x4	110x4	800	8	40	24250.00	24349	70
	850	90x3	116x5	850	8	20	25662.50	-	
	900	84x5	120x4	900	9	30	27612.50	27305^{+}	60
	950	90x4	118x5	950	9	10	28925.00		
	1000	85x5	115x5	1000	10	50	30312.50		
	1035	90x4 75x1	120x5	1035	10	Nil	31625.00		
480	200	85x1	115x1	200	2	10	5950.00		
	250	75x2	100x1	250	3	50	7500.00		
	300	90x2	120x1	300	3	Nil	8425.00	8751	120
	350	80x3	110x1	350	4	40	10237.50	10121^{+}	70
	400	90x2	110x2	400	4	20	11350.00	11531	80
	450	92.5x4	120x1	450	5	30	13025.00	12903^{+}	60
	500	90x3	115x2	500	5	10	14325.00	14428	40
	550	82.5x4	120x2	550	6	50	15530.00	15669^{++}	50
	600	90x4	120x2	600	6	Nil	16850.00	17134	60
	650	85x4	103.33x3	650	7	78	18875.00	18561^{++}	70

Table 5.3(Contd.)

1	2	3	4	5	6	7	8	9	10
	700	90x4	103.33x3	700	7	20	19925.00	19900^{+}	50
	750	90x3	120x4	750	7	Nil	21075.00	21465	90
	800	90x4	110x4	800	8	40	22700.00	22792^{+}	90
	850	90x3	116x5	850	8	20	24012.00	24362	110
	900	84x5	120x4	900	9	30	25850.00	-	-
	950	90x4	118x5	950	9	10	26975.00	-	-
	1000	85x5	115x5	1000	10	50	28375.00	-	-
	1035	90x4 75x1	120x5	1035	10	Nil	29500.00	-	-
500	200	85x1	115x1	200	2	10	5725.00	-	-
	250	70x2	110x1	250	3	50	7212.50	-	-
	300	90x2	120x1	300	3	Nil	8150.00	8264	90
	350	80x3	110x1	350	4	40	9825.00	9903	120
	400	90x2	110x2	400	4	20	11000.00	-	-
	450	82.5x4	120x1	450	5	30	12500.00	12388^{+}	60
	500	90x3	115x2	500	5	10	13875.00	-	-
	550	82.5x4	110x2	550	6	50	14987.50	15045^{++}	50
	600	90x4	130x2	600	6	Nil	16300.00	-	-
	650	80x4	110x3	650	7	70	18187.50		

Table 5.4 Unit Commitment and Saving in Water

Sl. No.	Load MW	Head ft.	No. of Machines scheduled		Discharges(cusecs)			Spinning Reserve MW
			Trial Cal. (Hand)	Optimal Cal.	Trial Cal. (Hand)	Optimal Cal.	Saving in water	
1.	550	320	70x4 90x3	71x4 88.5x3	22900	22778	122	35
2.	700	320	72x5 85x4	69.9x5 87.6x4	29175	29029	146	55
3.	550	360	85x2 90x2	90x2 85.5x2	13050	12863	187	54
4.	450	360	85x3 98x1 97x1	90x2 90x3	16525	16514	11	66
5.	550	400	85x3 75x1 110x2	82.9x4 109.5x2	18100	18031	69	50
6.	650	400	85x4 103x2 104x1	81.5x4 107.9x3	21440	21374	66	70
7.	650	440	85x4 113.3x3	81.3x4 108.3x3	19795	19809	-12	70
8.	550	480	82.5x4 110x2	87.6x4 100x2	15980	15669	311	50
9.	550	500	82.5x4 110x2	86.8x4 100.5x2	15300	15095	205	50

Cal = Calculation

(f) Programme has been fed for a fixed Nangal Fertilizer Factory load and spinning reserve. But it could be tried at other values as per requirement.

(g) Generation scheduling programme for one head condition for loads varying from 300-950 MW at 50 MW spinning reserve step, took in the final programme 35-40 seconds on a large digital computer IBM 360 at Dehradun.

(h) Performance curves were read for the safe zone portion only for determining the constants Ak_i and B_i.

(i) Levels of reservoir and tail race could be read and head worked out by adding a few statements in the main programme.

(j) From Table 5.4, it is seen that the significant saving can be effected by scheduling the generation by computer studies. This may be about 0.5-2 percent. However, this saving when calculated on yearly basis would have considerable amount of water to be used when required for irrigation use and additional head would amount to increment in energy generation through the plants.

5.9 Conclusion

Optimization technique and computer programmes have been developed to obtain optimal discharges and schedules for Bhakra Power Plants, under the varying conditions of tail race and reservoir levels, load, spinning reserve and Nangal Fertilizer Factory load. Long hand calculations would be impracticable for optimum scheduling as discussed in section 4.8. The analysed programming technique would help in conservation of water and energy to optimize generation from hydel stations and as such would be valuable contribution to power industry. The programmes could be further modified for scheduling the generation of hydro plants of the entire Northern grid through the application of microprocessor(42,112) control system.

CHAPTER VI

DAILY OPTIMAL OPERATION OF BALANCING RESERVOIR OF BEAS SATLUJ LINK HYDROELECTRIC PROJECT

6.1 Introduction

The Balancing Reservoir (BR) is an important component of Bhakra Beas System and located at Sundernagar (Fig.3.2 and 6.1). The objective of BR operation is to maximize the hydroelectric energy generation on hourly basis at Dehar power plant of Beas Satluj Link (BSL) project, meeting Bhakra-Beas system peaks and Beas to Satluj interstream water transfer requirements. This transferred water further maximizes energy generation at Bhakra Complex as reported in earlier Chapters. Typical day generation curve for Northern grid and Bhakra Complex is given in Fig.6.2.

The use of mathematical programming techniques for the optimization and simulation for hourly reservoir system operations for power generation purposes have been reported in the literature recently. However, in most of the work only techniques have been developed and reported. Field problems have been included for analysis by a few workers which are the major requirements for the planning, design and operational decisions especially in case of newly built large plants.

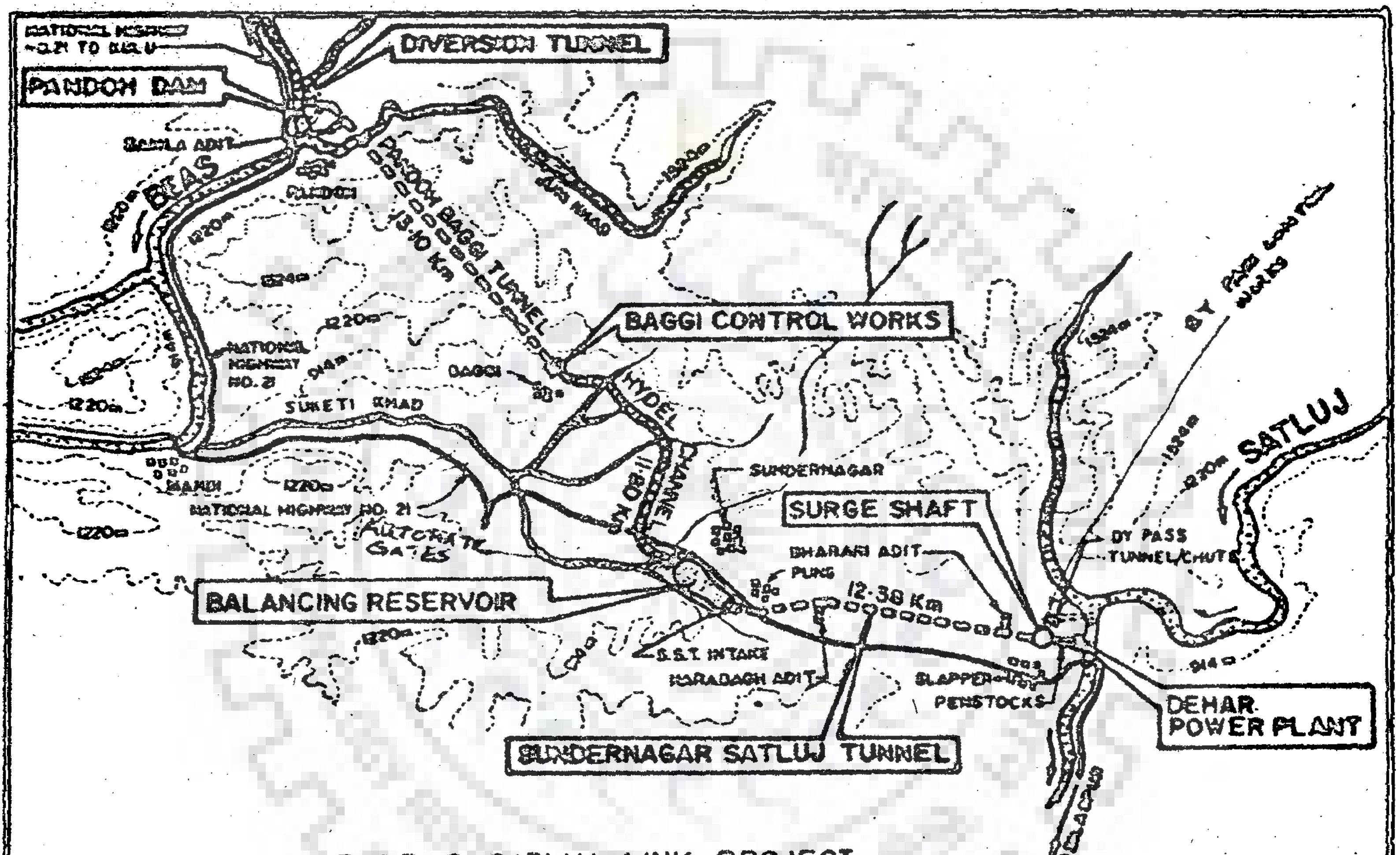


FIG. 6·1 DETAILS OF BEAS SATLUJ LINK PROJECT

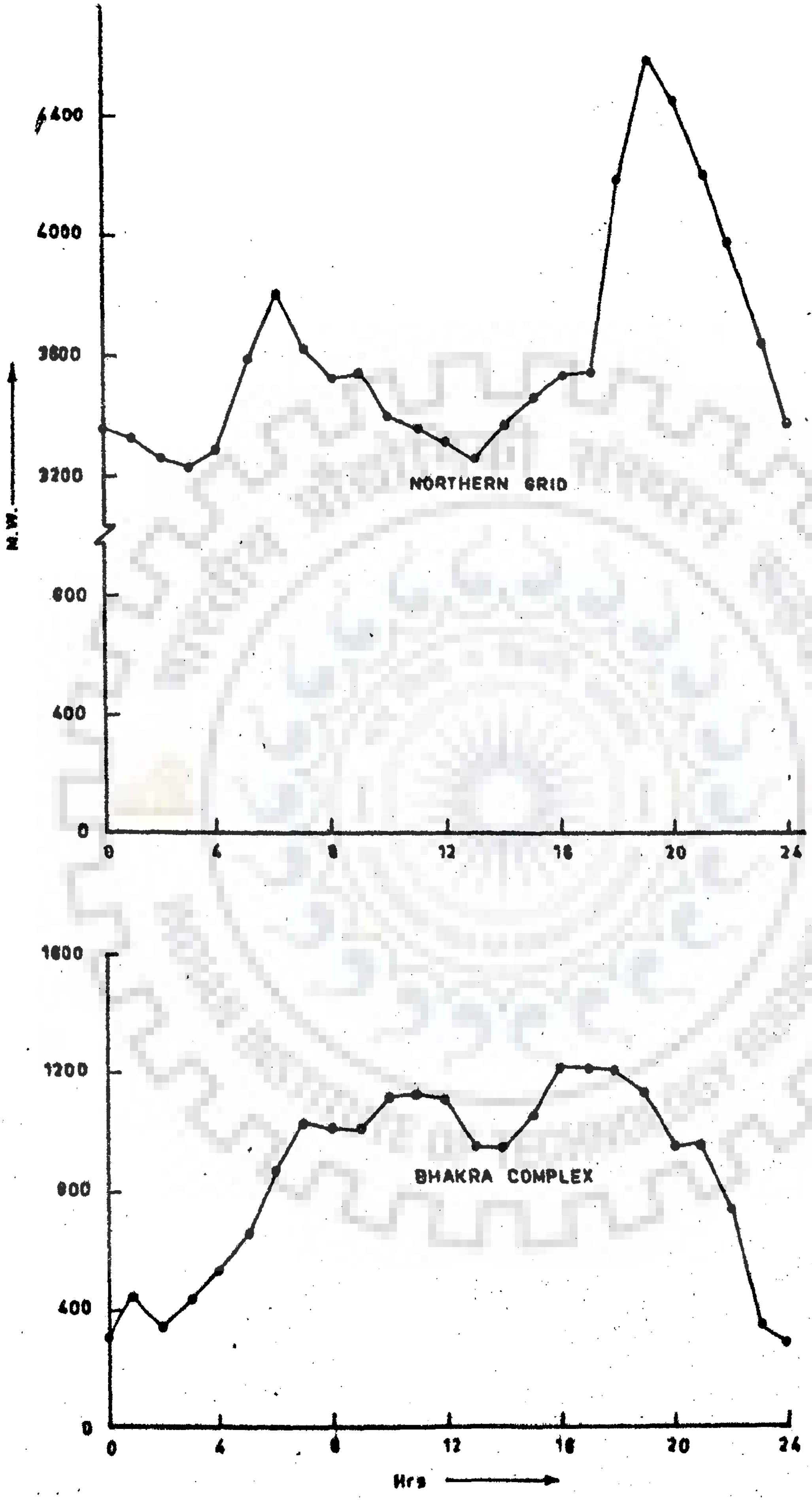


FIG 6·2 TYPICAL DAY GENERATION CURVE FOR NORTHERN GRID AND BHAKRA COMPLEX OCTOBER 79

Becker et al. (6) developed a hybrid optimization technique (LP-DP) to compute optimal policy each month. It was extended by Becker et al.(5) and Yeh et al.(115) to California Central Valley Project (CVP) for finding real time monthly and daily optimal operations. The basic idea is similar to Fults and Hancock (30). Hicks et al.(49) and Chu et al. (17) have developed Non Linear Programming algorithm for Real-Time hourly reservoir operations. Yeh et al.(117) have further reported real time hourly reservoir operation to CVP system. Linear Programming technique have been used for obtaining good feasible policy with better conformance with power schedule and Incremental Dynamic Programming Successive Approximations to obtain a somewhat more optimal solution over a 24-hr. day. Baxter et al. and Gagnon et al. (4,32) have applied Non Linear Programming techniques for determining optimal short term operating for major hydroelectric plants. Power pondage studies hourly, weekly (23,19) have been done for actual systems with Stochastic and Simulation approaches. Laufer and Morel Seytoux (73) have developed a technique for Alpine reservoir based on the solution of the system of equations given by Kuhn-Tucker conditions.

6.2 Objective of Study

The objective of the study of this subsystem is to develop procedures for determining optimal hourly releases from the balancing reservoir for hydro power production at Dehar Power Plant. The objective is to frame the schedules of regulation and maximize the sum of hourly power generation over a period of one day by regulating the balancing reservoir in such a planned schedule that peak load and base energy requirements set for the plant would be met alongwith project physical constraints. The developed technique would permit easy generalization for possible application at other facilities and inclusion of other reservoirs and plants on the two rivers- Beas and Satluj.

Stream flows and load demands are essential for these studies. The daily operation of the Pandoh weekly reservoir, daily balancing reservoir and Power Plant described herein are analysed by a hand calculations and optimization model. The constraints include generation upper and lower limits, open channel and tunnel capacities and hourly discharge variation rates, upper and lower limits on reservoir levels, variation in the set power schedules, tailwater variation, head losses in power tunnel and operation of control gates.

6.3 Schedules of Regulation

It is a summary of a regulation plan's recommendations. It consists of (a) a ' rule curve', (b) a number of ' Schedules', and (c) various pond elevations, outflow and river stage and water transfer system constraints. The schedules are very much similar to Annual Schedule of regulation. It also specifies the procedures for returning the pond to rule curve levels.

The rule curve is a pond elevation time diagram and guide line for reservoir operation. A typical rule curve is given in Fig.6.3. Mostly, the development of a rule curve is delayed until after the project is completed. This is unfortunate because it is difficult to accurately assess the true accomplishments of a project in the planning stage without knowing the rules which govern the operation of the project. Absence of rule curve also creates difficulty in the initial stages of operation. In a project where main purpose is power generation the pond levels at all times should be as high as possible to get the maximum energy and meet daily peaks. Unlike the annual rule curve, for daily operation a number of curves depending upon hydrologic conditions, power, and ; water transfer demands are required. The purpose in the ensuing sections is this.

6.4 Analysis Through Hand Calculations

The BR operation depends upon Beas inflows and weekly storage at Pandoh. Typical Beas river 10-daily inflows of dependable year are given in Table 6.1. It is observed that inflows for five months (May-Sept.) are more than the maximum capacity of water conducting components from river Beas to river Satluj. This limit is 212.38 cumecs. Therefore, 212.38 cumecs water, the full supply discharge at tail of hydel channel, could be transferred throughout the above period. The efficiency of transferring this discharge depends upon the uninterrupted and trouble free operation of

Table 6.1 Typical 10-Daily Inflows of Dependable Year of River Beas at Pandoh

Month	Period(Days)	Beas Inflows(cumec)
1	2	3
June	1-10	276.00
	11-20	340.99
	21-30	412.01
July	1-10	505.00
	11-20	575.00
	21-31	588.00
August	1-10	618.02
	11-20	657.01
	21-31	540.99
September	1-10	426.00
	11-20	311.00
	21-30	244.01
October	1-10	174.99
	11-20	133.99
	21-31	110.29
November	1-10	88.01
	11-20	82.01
	21-30	76.00
December	1-10	69.01
	11-20	64.99
	21-31	60.00
January	1-10	59.01
	11-20	57.00
	21-31	54.99
February	1-10	60.00
	11-20	60.00
	21-28	62.01
March	1-10	69.00
	11-20	89.99
	21-31	102.00
April	1-10	121.99
	11-20	145.01
	21-30	172.98
May	1-10	181.99
	11-20	206.99
	21-31	244.00

Source : BBMB

control works at the end of two long tunnels and hydel channel tail and control gates having automated controls. All civil, mechanical and electrical control works maintenance is planned for the lean period (November 11- March 10) when inflows are dropped to 70.79 cumec. Medium inflow period is October-November 10 and March 11- April when inflow is about 113.28 cumec (4000 cusec).

Real time optimal operation policy with the objectives as maximization of energy generation, secondly meeting the Bhakra-Beas system peak and transferring maximum water from one basin to the other would be different with the available 4 machines and in the near future when two more 165 MW machines are added in the Power Plant. In the initial attempt the operational policy for fulfilling the above objectives with hand calculations has been considered below for the ultimate state. The project is having component wise limitations and operational constraints given in Appendix VI.

6.4.1 High inflow period

During high inflow period, balancing reservoir should be maintained at maximum EL 842.47 m. However, when 4 machines running would require 4 x 56.63 = 226.53 cumec (approximately) of water, the level in balancing reservoir would start falling down at a rate of approximately 0.3048 m for every 28.32 cumec/hr. discharge. Elevation and Capacity relationship for balancing reservoir **is given** in Table 6.2 and

Table 6.2 Balancing Reservoir Elevation and Capacity Relationship

Sl.No.	Elevation (in m)	Storage Volume (in Hm)
1.	833.32	0
2.	833.63	12.34
3.	835.15	74.01
4.	836.68	135.69
5.	838.20	197.36
6.	839.72	259.04
7.	841.25	320.71
8.	842.47	370.00

Source : BBMB

Appendix VII and for Pandoh reservoir in Appendix VIII. In a day 3.67m level will fall down. Hence, reducing effective head on the turbines. To maintain this head at a constant maximum elevation for optimal energy generation, this could be achieved in two or more ways. However, below are given two best alternatives only.

a) run three machines at full and one machine at 75 percent rated capacity (169.90 + 42.48 = 212.38 cumecs) during 24 hours i.e. plant will run as base load.

b) run three machines at full generation for 24 hours in a day and fourth machine for 18 hours (42.48x24/ 56.63 = 18 hrs) in a day at full generation.

Alternative (b) would be able to contribute additional generation of (165/4 = 41.25 MW) at system peak. Also during light load conditions thermal units could take this load causing less variation in their production pattern.

With six machines availability, the schedule could run all the machines for 7½ hours during two peaks in the morning and evening and 2¾ machines (453.75 MW with 155.74 cumec discharge) for rest of the period in a day. Hourly balancing reservoir level change or the tentative rule curve is indicated in Fig.6.4.

6.4.2 Low and medium inflow period

This period runs October 11 through May 10. Inflow in Beas river fluctuates from 56.63 cumec to 184.06 cumec approximately which is less than the channel capacity. In this period the power plant would operate primarily for peaking purposes and it could be possible to transfer the complete inflow of river Beas to river Satluj. However, since the inflow is random, hourly operation of balancing reservoir would be different and depend upon the inflow from time to time. For two cases when inflow is 113.28 and 70.79 cumec, rule curves for balancing reservoir are worked out and plotted in Figs. 6.5 and 6.6.

With inflow 113.28 cumec, it is possible to run four machines in the morning and six machines for evening peaks respectively. However, most of the other hours one machine operates. Regulation at Baggi control point would be required five times to increase or decrease the inflow to balancing reservoir in 24 hours, in order to maintain maximum level. During the lowest inflow (70.79 cumec) period , seen in Figs.6.5, it would be desired to run four machines at the peaks, no generation from 2300 to 0800 hrs and one machine in the rest of the period of the day. The reservoir level varies between 842.47 m to 839.11 m. However, it could be improved by altering the generation schedule in which Baggi control functions four times during the day. Level variation in Pandoh reservoir would also take place which have been considered in the 10-daily calculations. The difference of Beas inflow and inter-transfer of water to Satluj at Pandoh is sufficient to keep the storage content within minimum and maximum limits. For this reason balancing reservoir hourly optimization programme did not include Pandoh reservoir.

6.5 Mathematical Representation of Problem

The objective is to develop an hourly programme for a day and determine the optimal operating policy for balancing reservoir and inturn maximize the energy generation and meet the system peaks. Mathematically :

$$\text{Maximize} \sum_{t=1}^{T=24} PPG_t \tag{6.1}$$

Subject to the following constraints :

1) Continuity at Pandoh and Sundernagar Ponds :

a) $$PRS_t = PRS_{t-1} + BFLOW_t - RELPB_t - RELD_t - EVPR \tag{6.2}$$

b) $$RELPB_t = RELBR_t + RELST_t \tag{6.3}$$

c) $$BRS_t = BRS_{t-1} + RELBR_t - QB_t - EVBR \tag{6.4}$$

d) $$QB_t = QC_t + QP_t \tag{6.5}$$

2) Minimum and Maximum Pond Levels at these ponds:

$$833.32 \leq BRL_t \leq 842.47 \text{ m} \tag{6.6}$$

$$883.92 \leq PRL_t \leq 896.42 \text{ m} \tag{6.7}$$

3) Storage Constraints :

$$PRST \leq 4100 \text{ hm} \tag{6.8}$$

$$BRST \leq 370 \text{ hm} \tag{6.9}$$

4) Capacity constraint in Pandoh Baggi Tunnel

$RELPB_t \leq 254.85$ cumec (6.10)

5) Release for silt ejection at Baggi

$RELST_t \leq 42.48$ cumec (6.11)

6) Capacity and fluctuation constraints in Sundernagar Hydel Channel:

a) $RELBR_t \leq 212.38$ cumec (6.12)

b) Rate of rise in channel discharge

$RELBR_t = 28.32$ cumec/hr. (6.13)

c) Rate of fall in channel discharge

$RELBR_t = 16.99$ cumec/hr. (6.14)

7) Capacity constraints in Sundernagar Slapper Tunnel (Power Tunnel) by pass tunnel and Chute :

$QB_t \leq 403.52$ cumec (6.15)

$QC_t \leq 212.38$ cumec (6.16)

This is a large tunnel, head loss affects head on machines which has been taken care of in the optimization programme.

8) Penstock headers capacity constraints :

$QD \leq 113.28$ cumec in each header (6.17)

Since three sub-headers are there each serving two machines.

9) Tail water level constraint in the power plant:

It is the effect of machine discharge and Satluj river inflow variations.

10) Power plant and machine generation constraint :

$$0 \leq PPG_t \leq 990 \text{ MW} \quad (6.18)$$

$$140 \leq PG_t \leq 165 \text{ MW} \quad (6.19)$$

11) Peaking Constraint :

Power Plant should meet the two normal daily peaks of Bhakra-Beas System between 8-11 AM and 5-9 PM by running maximum number of machines.

Apart from the above mathematically represented constraints the following operational and structural guide lines have been considered in the overall operation strategy.

12) In case of sudden load reduction in the power system, transmission line interruption or power plant machine failure, control gates at by-pass chute should be set to operate automatically for transferring water to river Satluj.

13) Minimum time between the two starts of the plant machines should be more than 1 hour as gathered from the experience with these machines by the field engineers.

14) To minimise the effects of cavitation, machines should be loaded above 85 percent of their rating or for short intervals at lower rating.

15) Operation of control gates at Baggi control works should be limited to once in four hours.

16) It takes 45 minutes for the water discharge from Baggi control works to Balancing Reservoir approximately

and 15 minutes to power plant from Balancing Reservoir. However, this delay time is not considered.

Computer optimization flow diagram for determining a number of alternatives is given in Fig.6.7. This optimization programme has been developed to form a sub-routine of Bhakra-Beas system optimization programme discussed in Chapter IV, ultimately. The power generated in the sub-routine during an interval -10 daily or less would further maximize the generation from Bhakra-Beas reservoir system.

6.6 Solution Technique, Results and Analysis

The formulated problem has been solved by iterative optimization technique with the objective in equation 6.1 and various constraints. A computer programme was constructed for the flow chart given in Figure 6.7. It was run for three different inflow periods with changes in load demands, and step-sizes for limiting flow and generation. Achieved generation and Balancing reservoir levels during a day have been given in Tables 6.3, 6.4 and 6.5.

Initial flow and generation step sizes were selected as 14.16 cumec and 41 MW respectively. It is observed that as the step sizes reduce , difference between the total inflow and outflow from BR during 24 hours reduces to zero and generation is maximized (Sr. No.6,7, and 8 of Table 6.5 and Sr. No.5 through 8 of Table 6.3).

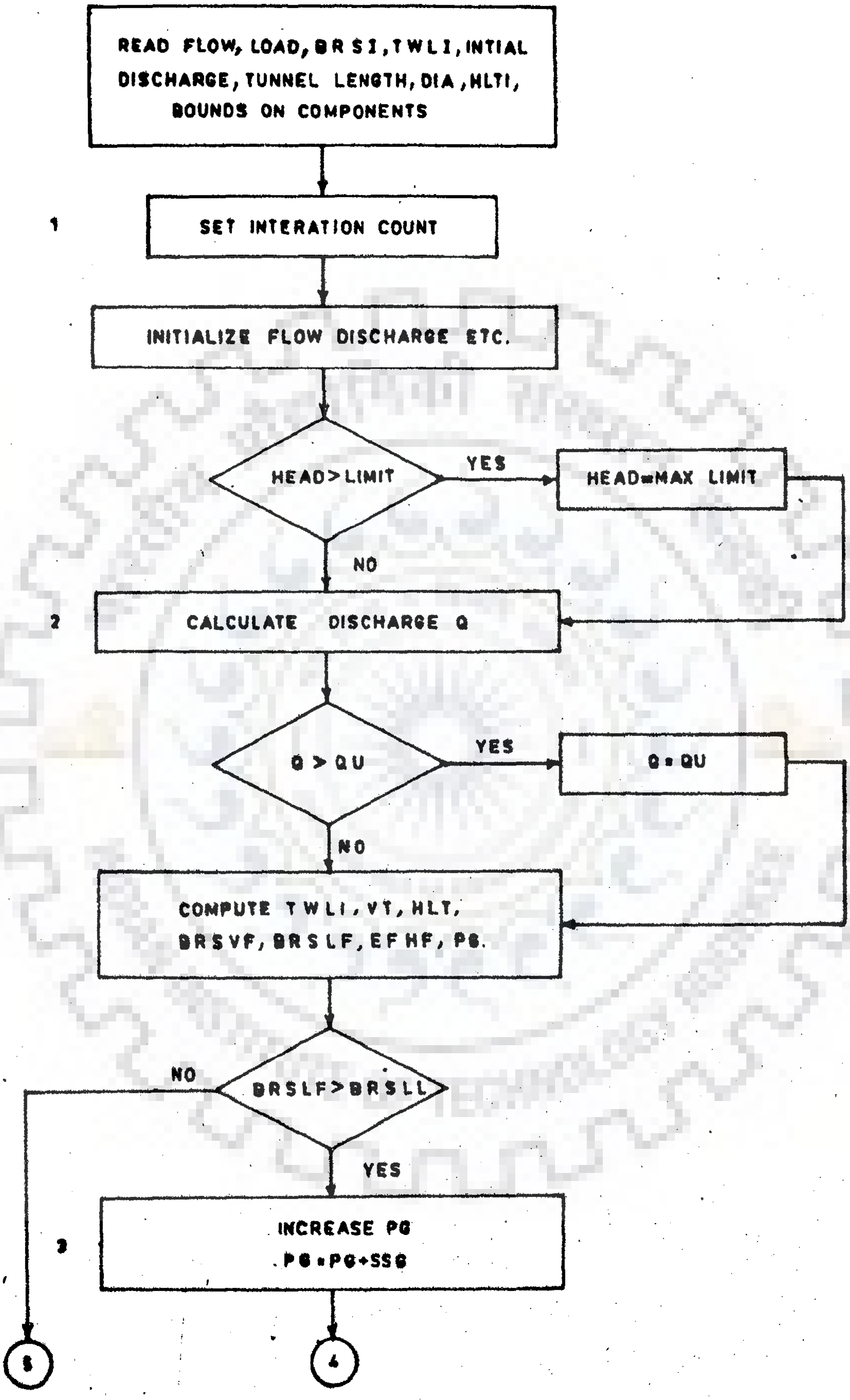


FIG. 6·7 BSL HOURLY OPTIMIZATION STUDY FLOW CHART

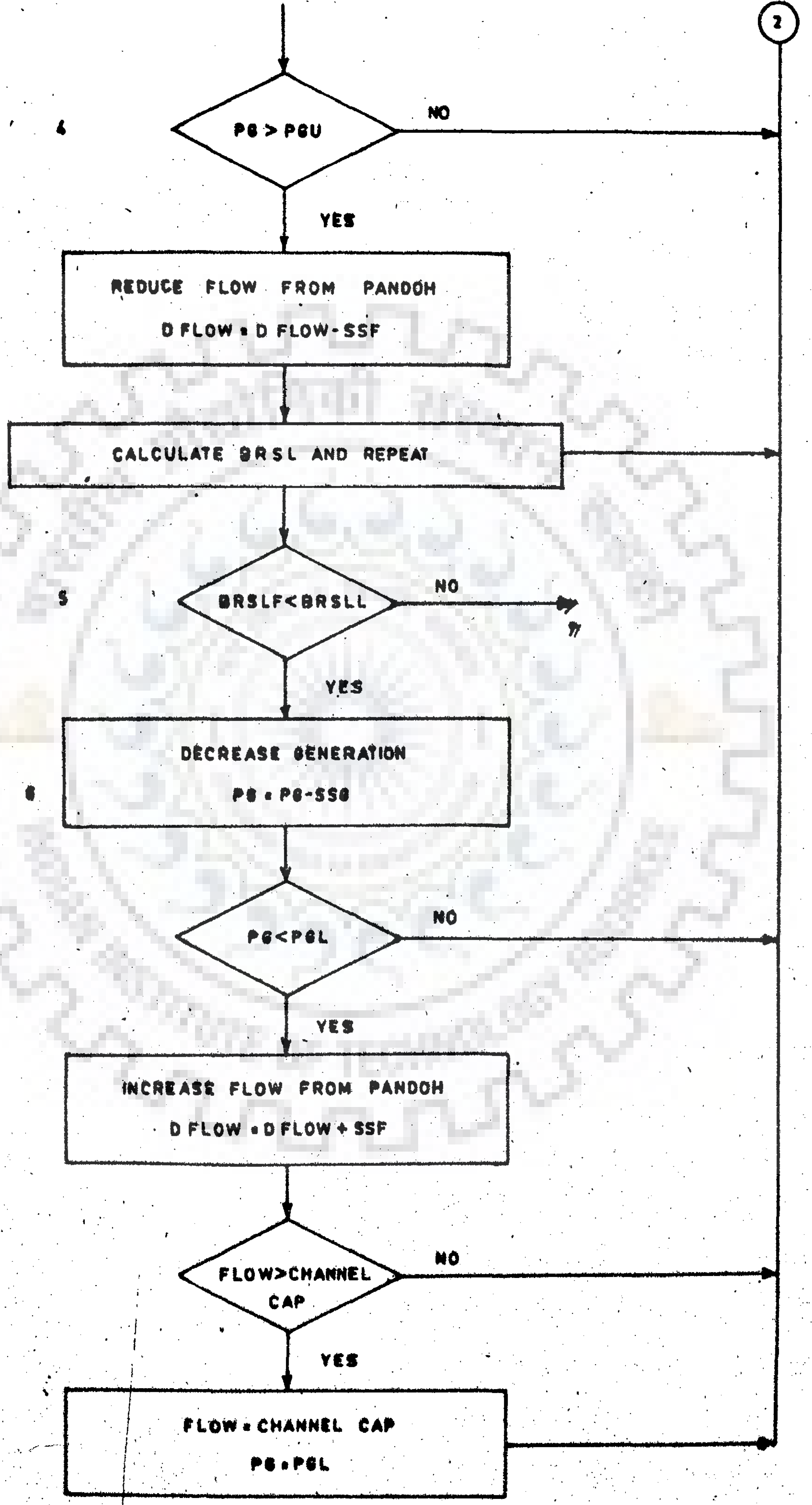


FIG [illegible] BSL HOURLY OPTIMIZATION STUDY FLOW CHART

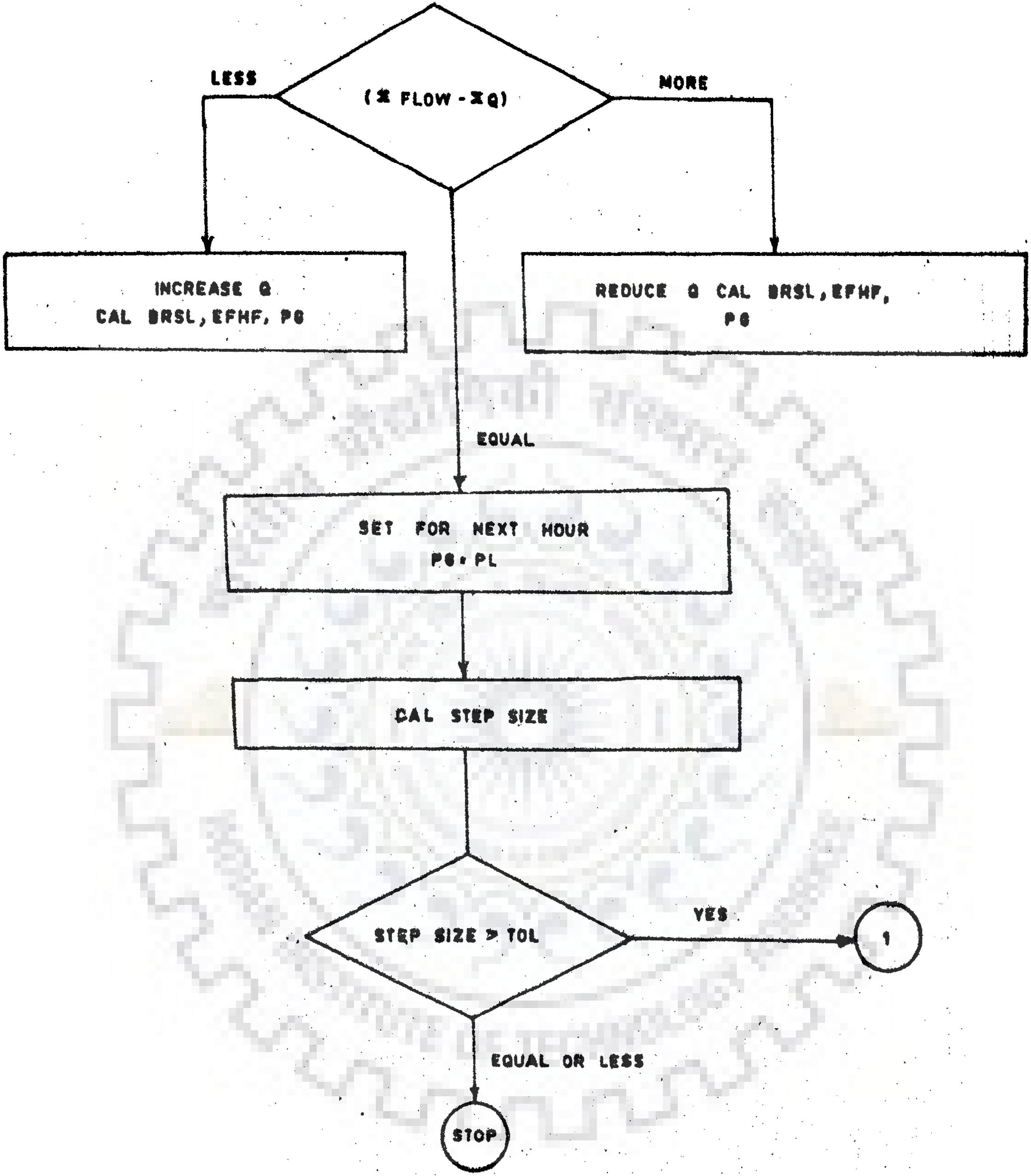


FIG. 6.7 BSL HOURLY OPTIMIZATION STUDY FLOW CHART

Table 6.3 High Inflow Optimization Study Results

Sl. No.	Inflows (cumec) hrs.	Outflows (cumec) hrs.	BR minimum level (m)	BR maximum level (m)	Generation (MWH)	Flow step-size (cumec)	Generation stepsize (MW)
1.	5097.03	5393.17	833.32	839.11	13790	14.16	41
2.	5097.03	5112.47	834.54	842.47	13741	14.16	41
3.	5097.03	4991.27	834.08	842.47	13285	14.16	41
4.	5097.03	5101.71	834.76	842.41	13305	2.83	20
5.	5097.03	5100.03	834.76	842.44	13285	1.42	10
6.	5092.79	5092.79	834.88	842.47	13284	1.42	10
7.	5096.16	5096.16	834.85	842.47	13287	0.028	1
8.	5096.72	5096.72	834.85	842.47	13289	0.028	1
9.	5079.93	5079.93	835.91	842.16	13475	0.110	1
10.	5082.87	5082.87	836.65	842.28	13496	14.16	1

Table 6.4 Medium Inflow Optimization Study Results

Sl. No.	Inflows (cumec) hrs.	Outflows (cumec) hrs.	BR minimum level (m)	BR maximum level (m)	Generation (MWH)	Flow step-size (cumec)	Generation step size (MW)
1.	2718.42	2724.05	834.74	842.47	7000	14.16	41
2.	2718.42	2721.39	833.32	842.47	6998	14.16	41
3.	3015.75	3025.17	833.32	842.47	8040	14.16	41
4.	3015.75	3016.25	833.38	842.41	8025	2.83	20
5.	3015.75	3016.74	833.35	842.47	8025	1.42	10
6.	3497.13	3497.13	834.97	842.44	9206	0.028	1

Table 6.5 Low Inflow Optimization Study Results

Sl. No.	Inflows (cumec) hrs.	Outflows (cumec) hrs.	BR minimum levels (m)	BR Maximum levels (m)	Generation (MWH)	Flow step-size (cumec)	Generation stepsize (MW)
1.	1755.64	2567.23	833.32	842.47	6725	14.16	41
2.	1738.65	2095.62	833.48	842.47	5970	14.16	41
3.	2548.52	2725.81	835.30	842.47	7370	14.16	41
4.	2548.52	2584.45	835.30	842.47	6880	14.16	41
5.	2548.52	2612.68	835.67	842.47	6930	2.83	20
6.	2547.92	2547.92	834.82	842.47	6787	2.83	20
7.	2548.23	2548.23	834.82	842.47	6787	0.11	1
8.	2530.82	2530.82	832.77	842.47	6773	0.028	1
9.	2421.09	2421.09	836.37	842.47	6606	2.83	1
10.	2418.26	2418.26	836.37	841.55	6583	2.83	1

A few of the important optimization results have been plotted in Figs.6.8 through 6.21 for three different flows in BR. It is observed that the rule curves of Figs.6.9,6.10, 6.12, 6.13, 6.14, 6.15 and 6.17 try to full the BR levels in the end of 24 hours period. Energy maximization has been achieved but operation of control gates at Baggi control works is not reduced.

These all three daily requirements - maintaining high level and keeping BR full at the end of period, maximum power generation and operation of control structures in limits have been resulted in Figs.6.9, 6.14 and 6.17 for three flow periods under study respectively.

A typical schedule of regulation is prepared and given in Table 6.6. The optimization results were also compared with the collected operation data. It is only commented that to achieve optimum power generation there is a need for adopting the optimization study for hourly operation under complex site conditions. This study would provide additional information and benefits and ease in daily operation planning to the regulation engineers of Bhakra Beas System.

Augmented inflows at Bhakra effected by Beas river water transfers are given in Table 6.7. These will further generate more power and meet water requirements of Bhakra Beas System. Pandoh reservoir storage content variation during high, medium and low inflow periods is evaluated in Appendix IX.

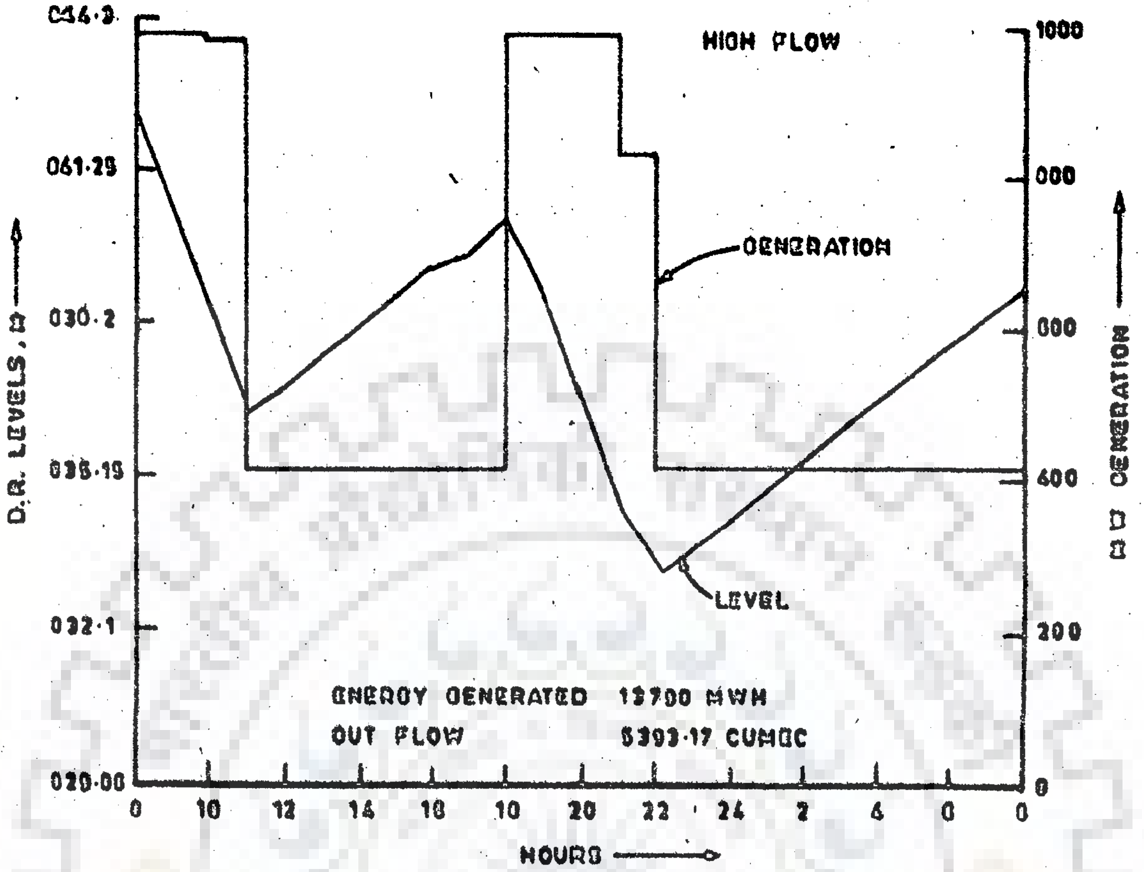

HIGH FLOW
GENERATION
LEVEL
ENERGY GENERATED 13700 MWH
OUT FLOW 5393·17 CUMEC
D.R. LEVELS, M
046·3
061·25
030·2
035·15
032·1
020·00
MW GENERATION
1000
800
600
400
200
0
HOURS
8
10
12
14
16
18
20
22
24
2
4
6
8

FIG. 6·8

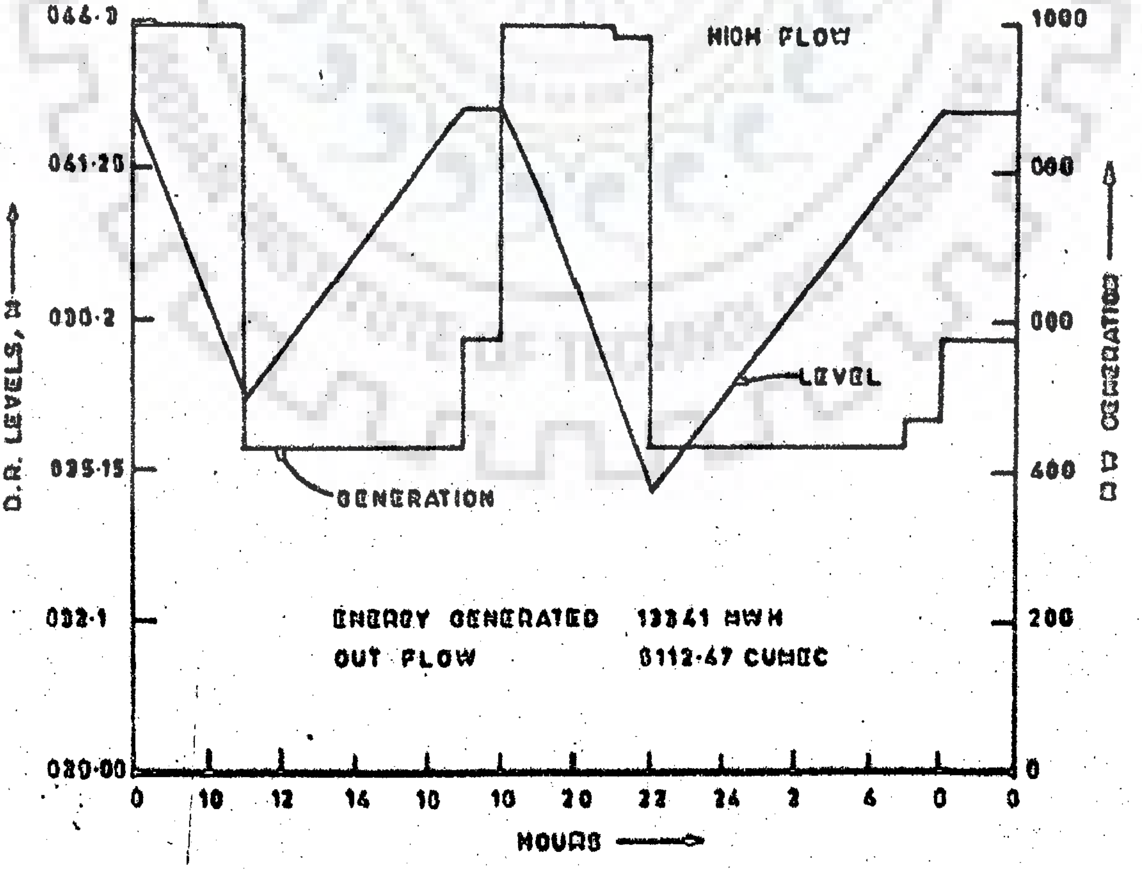

HIGH FLOW
LEVEL
GENERATION
ENERGY GENERATED 13341 MWH
OUT FLOW 8112·47 CUMEC
D.R. LEVELS, M
046·3
041·25
030·2
035·15
032·1
020·00
MW GENERATION
1000
800
600
400
200
0
HOURS
8
10
12
14
16
18
20
22
24
2
4
6
8

FIG. 6·9

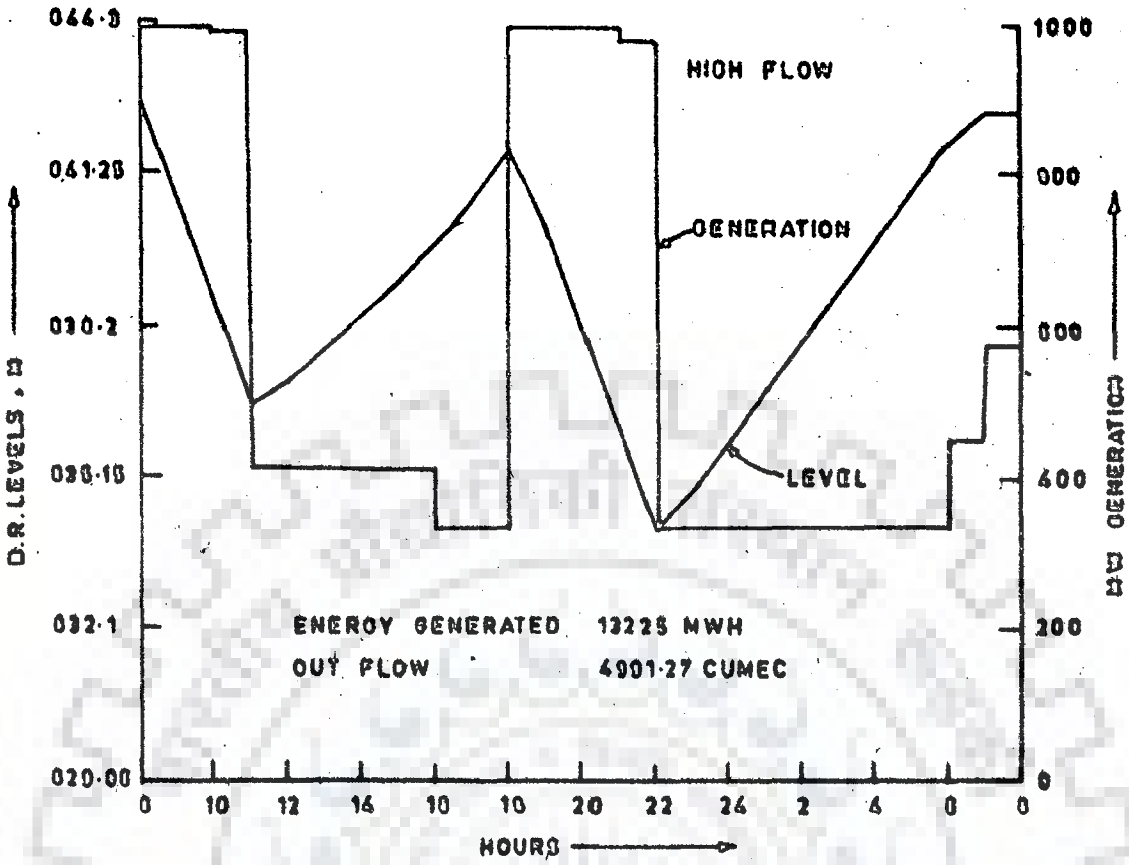


FIG.6·10

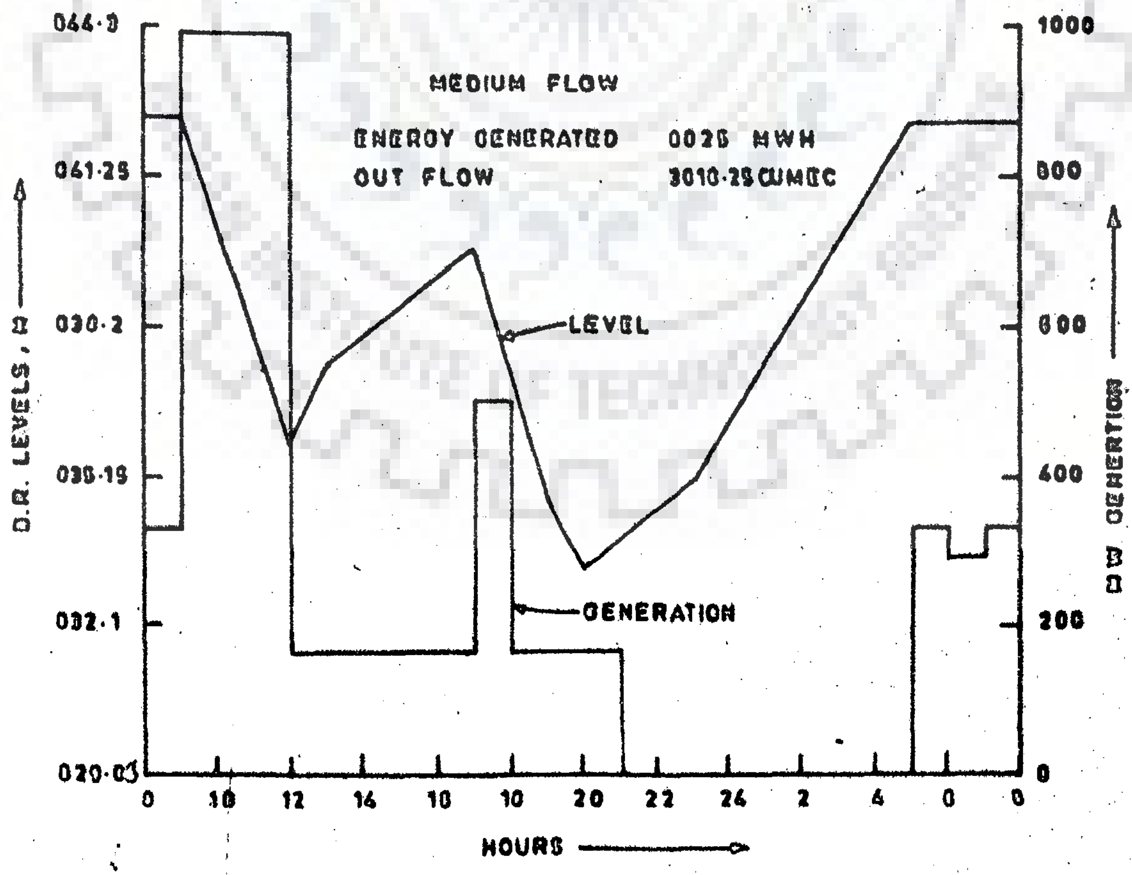


FIG.6·11

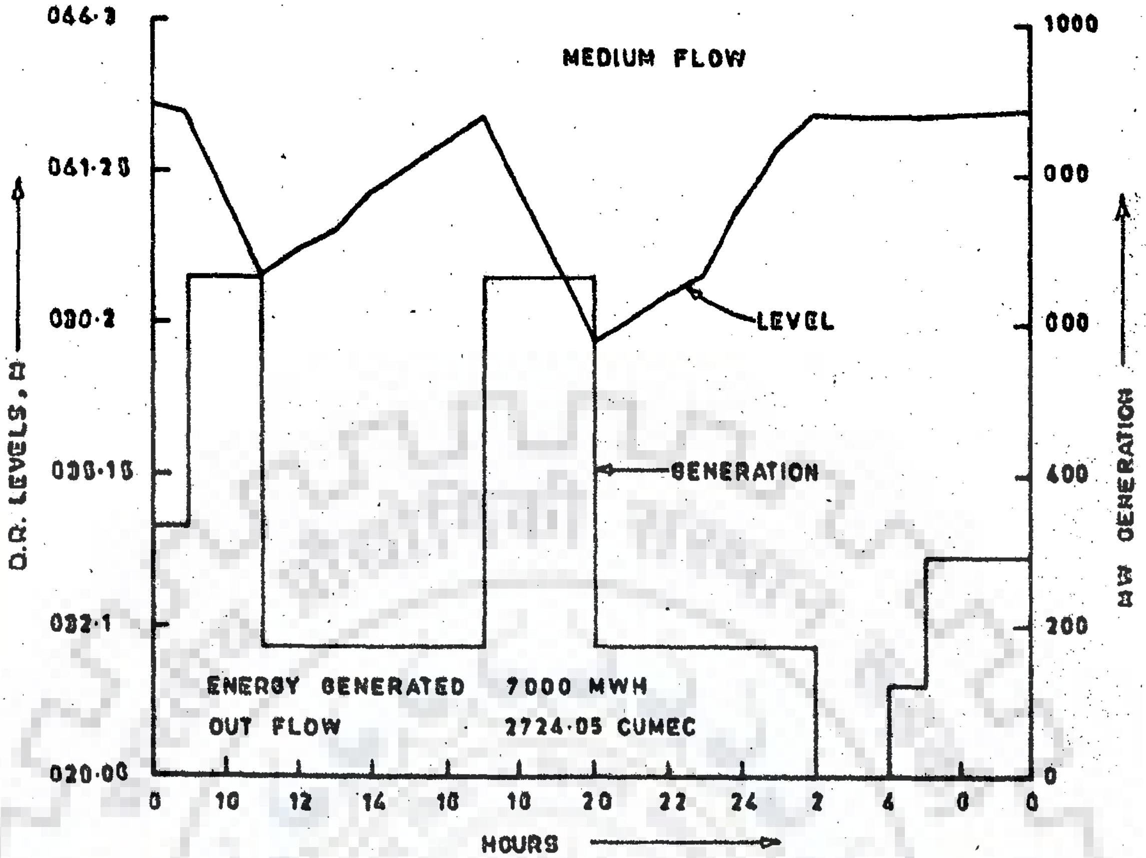


FIG. 6·12

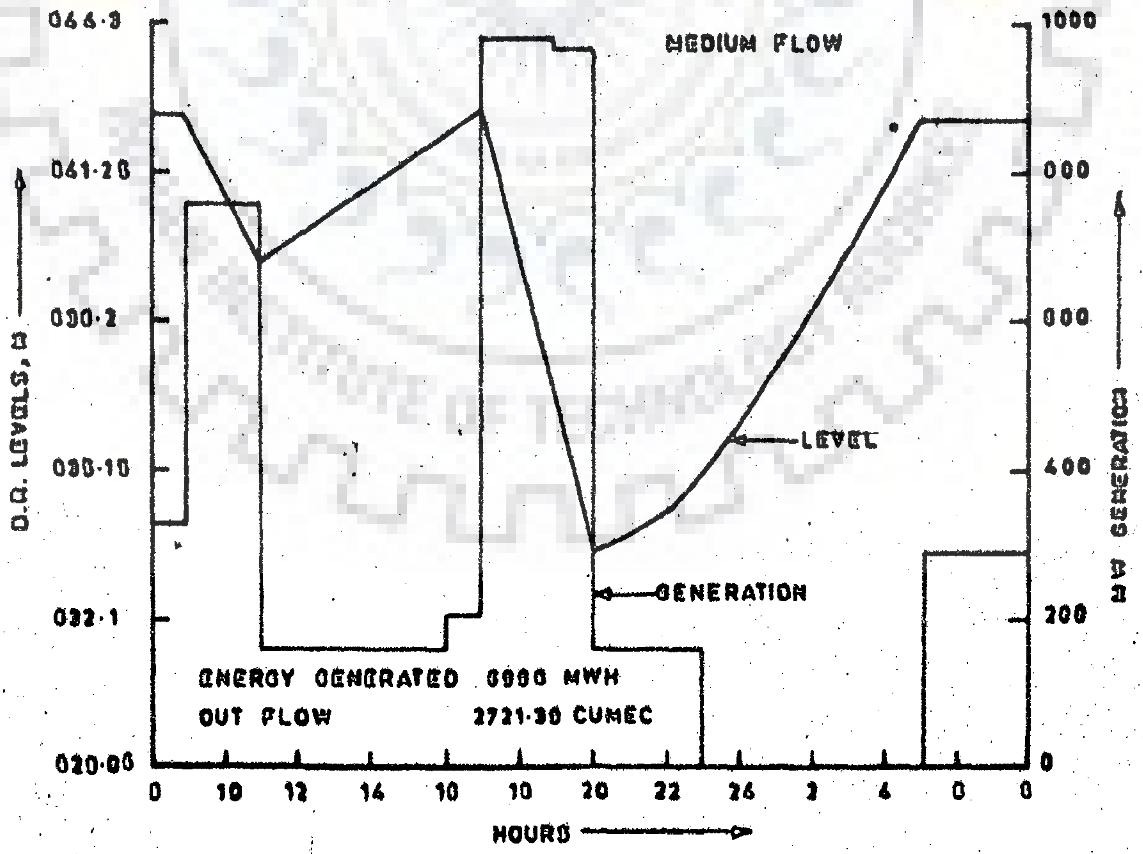


FIG. 6·13

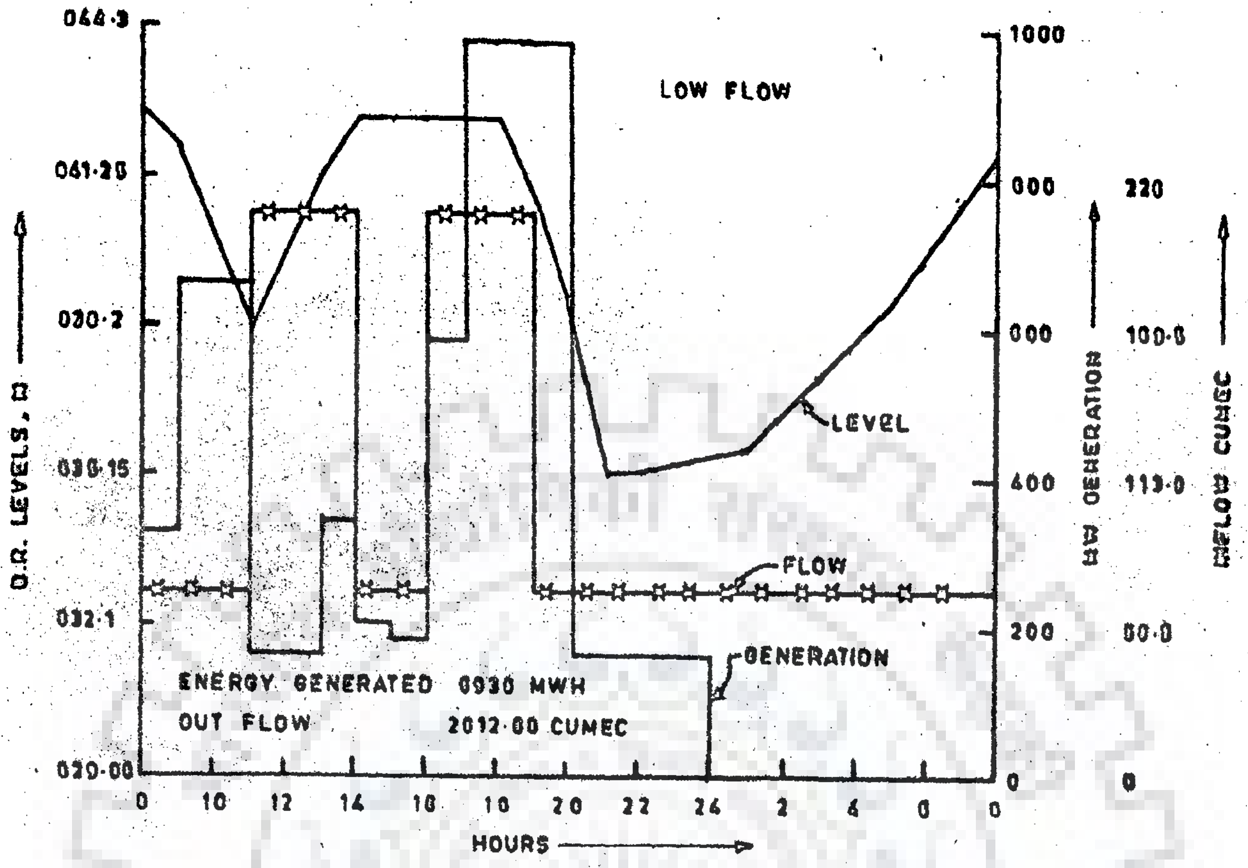


FIG. 6·16

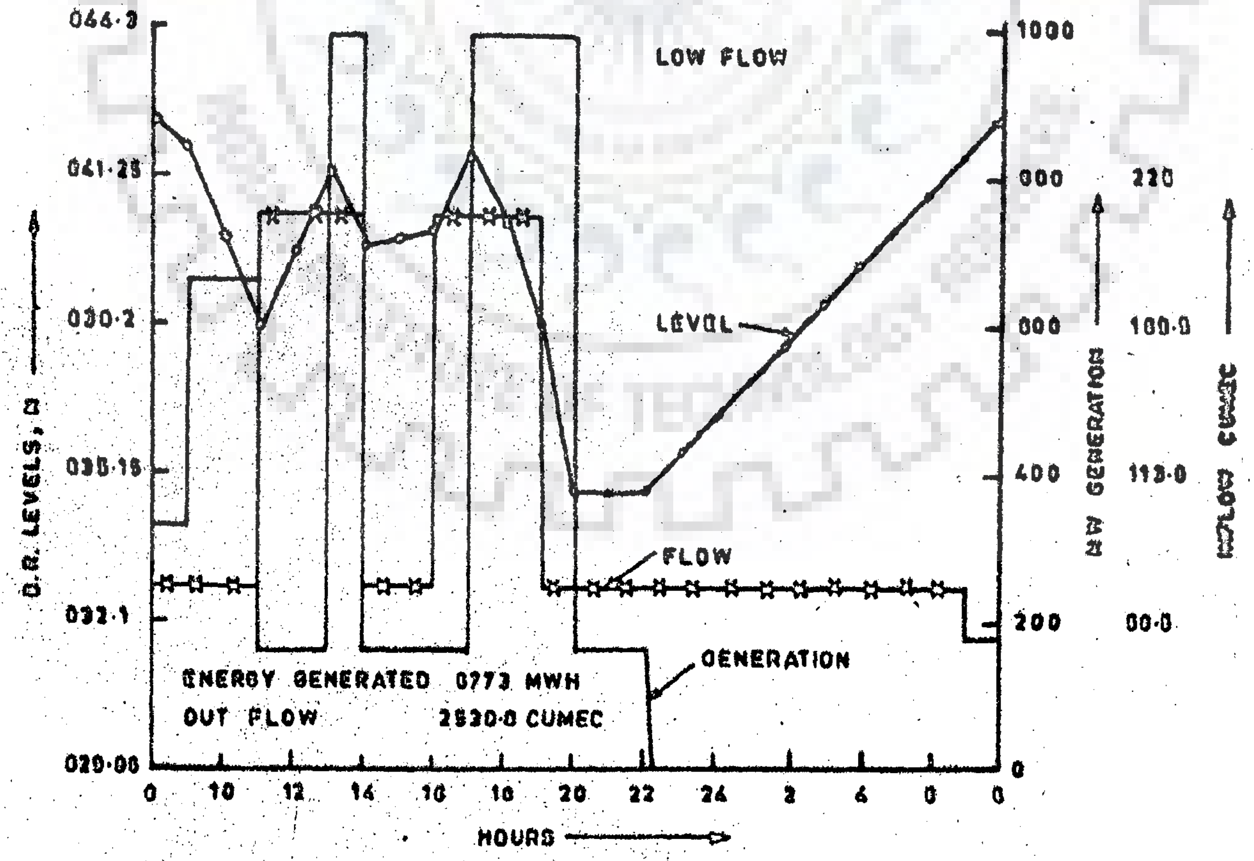


FIG. 6·17

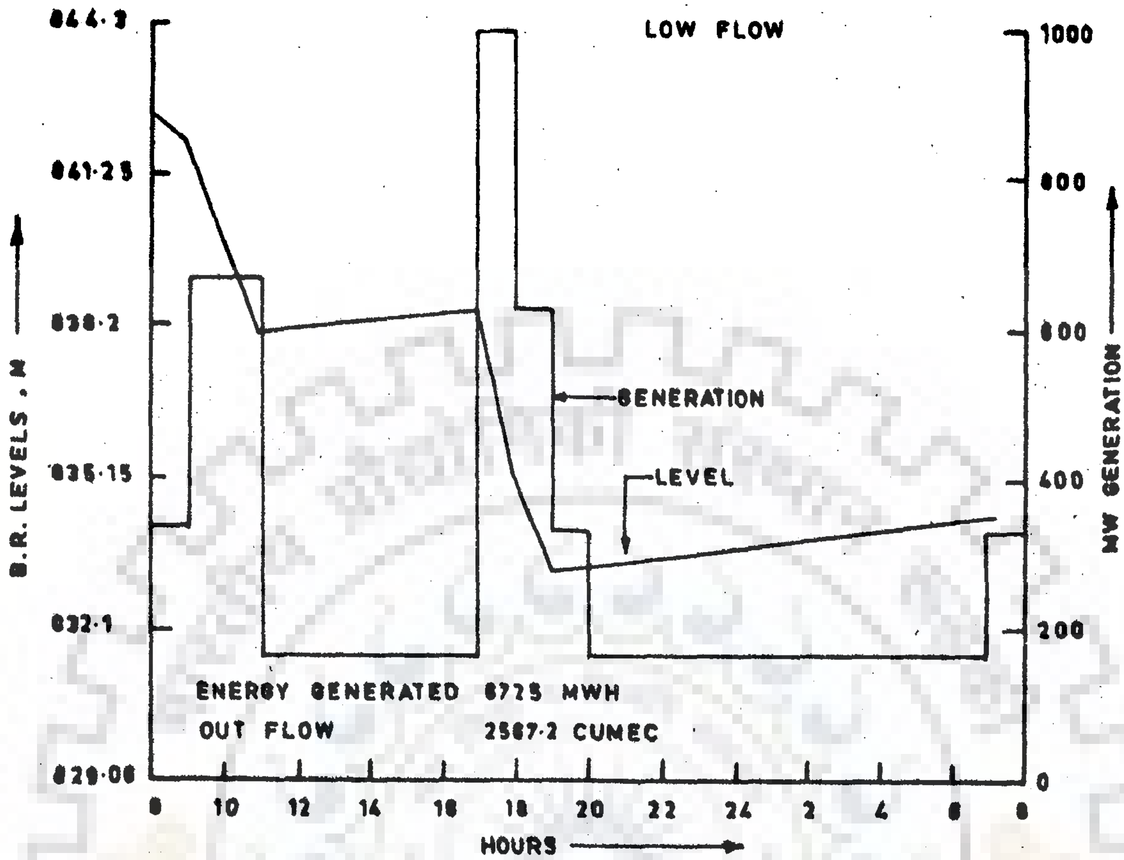


FIG. 6·18

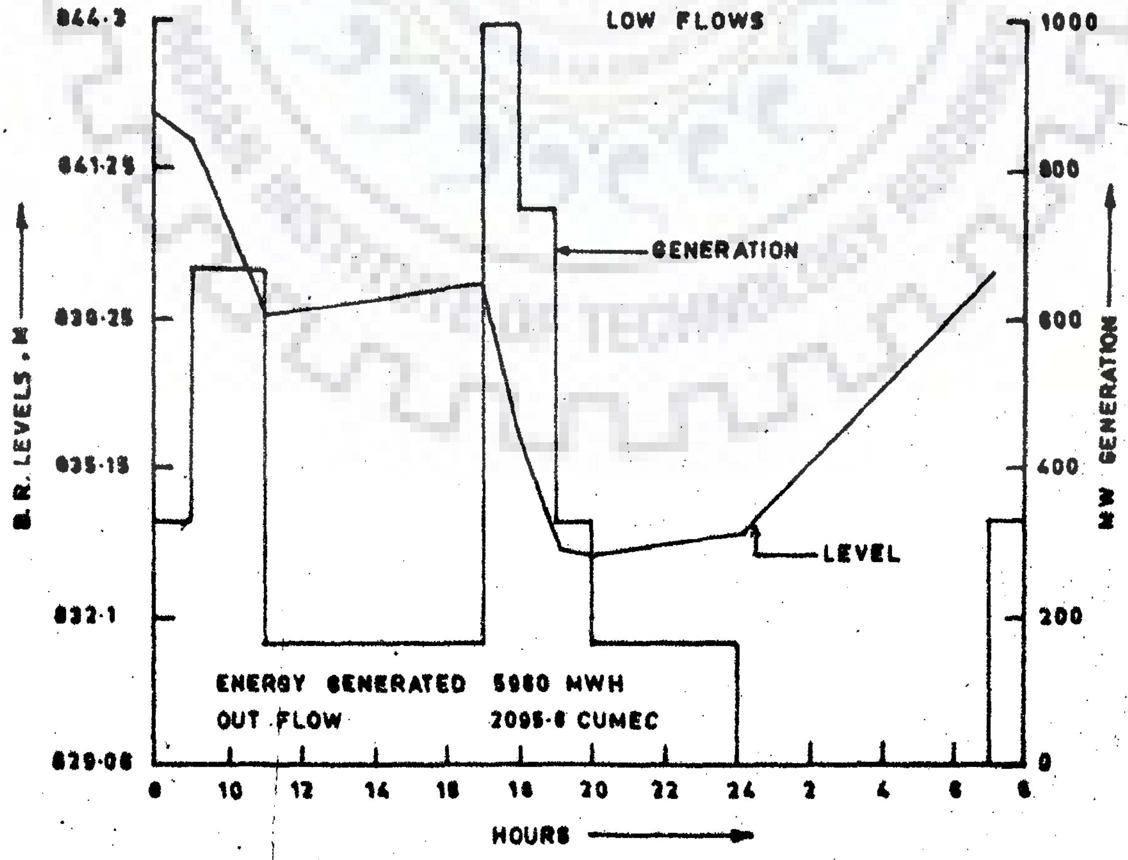
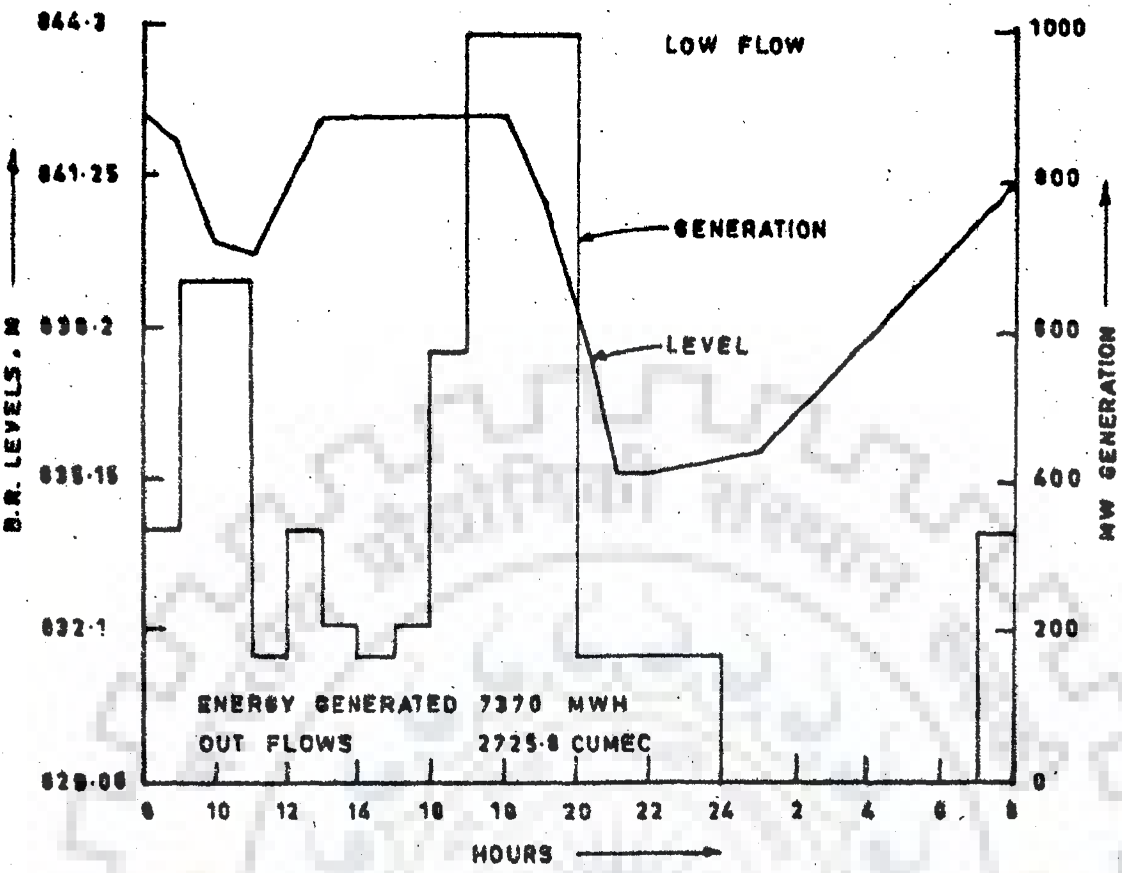
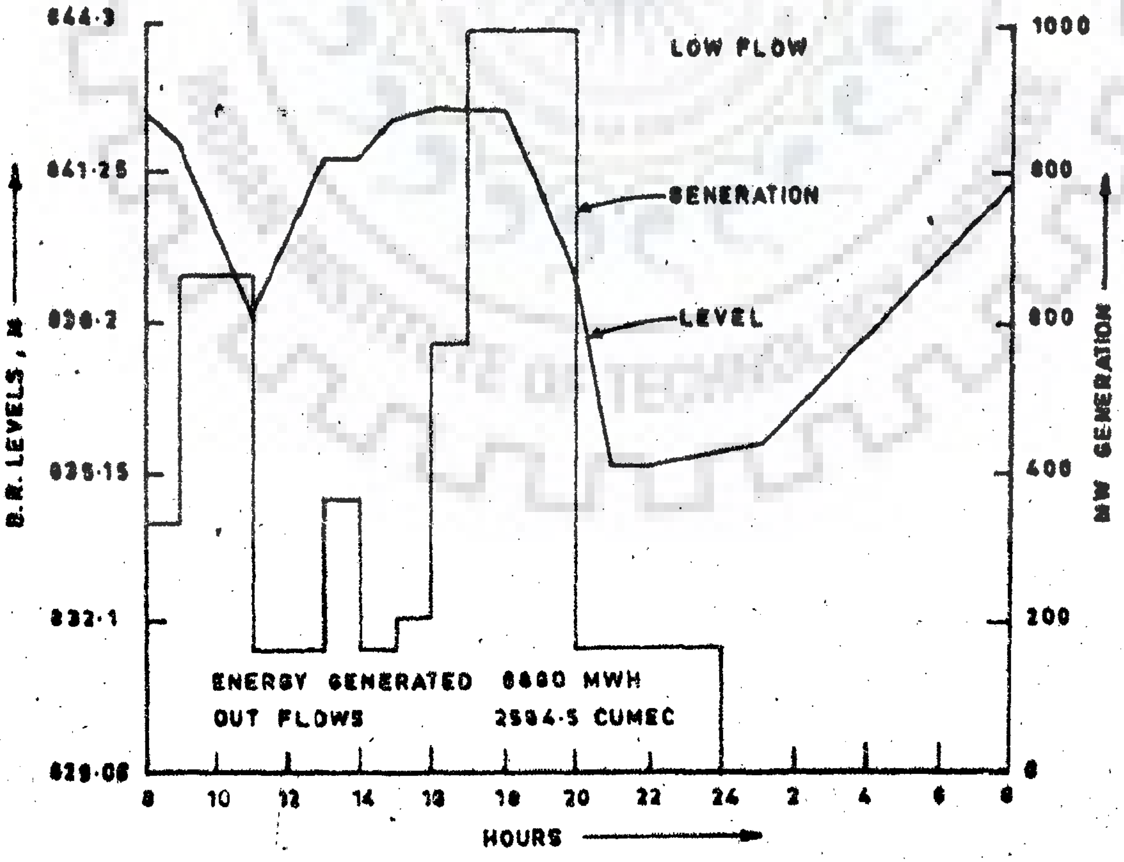


FIG. 6·19



ENERGY GENERATED 7370 MWH
OUT FLOWS 2725·8 CUMEC

FIG. 6·20



ENERGY GENERATED 6880 MWH
OUT FLOWS 2594·5 CUMEC

FIG. 6·21

Table 6.6 Optimization Study Schedule of Regulation

Schedule	Range in Pond Elevation	Time of Day	Regulation
A	Maximum Elevation	8AM-11AM	Open Baggi Gates releasing flows required for meeting morning system peak by running all machines at maximum capability.
B	Filling BR	11AM-5PM	Adjust Baggi Gates as per flow requirement for pond filling. Reduce generation.
C	Maximum Elevation	5PM-9PM	Open Baggi Gates releasing flows required for meeting evening system peak by running all machines at maximum capability.
D	Filling BR	9PM-8AM	Adjust Baggi Gates as per flow requirement for pond filling and reduce generation so that withdrawal from Pandoh reservoir does not exceed, a preset value. In high flow period By-pass chute regulation may be required, however, this contingency could be tackled by starting additional machines. BR Siphon escape comes into operation in case pond level rises.

Table 6.7 Augmented Inflows at Bhakra Effected by Beas Water Transfers

Period	Satluj Inflows at Bhakra (cumec)	Beas water Transfers to Satluj (cumec)	Augmented Inflows at Bhakra (cumec)
June (11-20)	707.49	212.38	919.87
June (21-30)	857.89	212.38	1070.27
July	1233.40	212.38	1445.78
August	1293.91	212.38	1506.29
September (1-10)	821.10	212.38	1033.48
September (11-20)	582.19	212.38	794.57
September (21-30)	366.11	212.38	578.49
October	233.81	113.28	347.09
November (1-10)	153.79	113.28	267.07
November (11-30)	153.79	70.79	224.68
December	122.89	70.79	193.69
January	109.38	70.79	180.18
February	108.71	70.79	179.49
March (1-10)	124.19	70.79	194.99
March (11-31)	124.19	113.28	237.48
April	162.59	113.28	275.88
May	314.29	212.38	526.67
June (1-10)	524.28	212.38	736.67

6.7 Conclusions

Procedures for operating the newly constructed large power project in optimal manner during different periods have been developed and discussed. Balancing Reservoir Rule curves within the structural constraints have been determined with the six machines at ultimate stage with the objective of meeting two normal daily Bhakra-Beas system peaks, maximum energy generation and to transfer optimum water from one river system to the other on which Bhakra power and irrigation project operates on downstream. Results compared with the so far operation records are very much encouraging and would help to generate more power by maintaining maximum level and storage.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Three case oriented studies - medium range, short range and hourly study for Bhakra - Beas multireservoir system have been carried out based on available data. The developed methods and operation analysis will generally apply to all multireservoir system analysis.

In the medium range study the system is modelled for the analysis of present operations and for generating alternatives to facilitate decision makers to operate the system optimally. The present method of operation on the basis of a few hand calculated water power tables prepared by regulating engineers will become more and more difficult and hence uneconomical as complexities of interconnection both in reservoir and operation system increase. The problem is formulated by multilevel hierarchial approach, generalised reduced gradient method used for reducing variables and eliminating equality constraints and solved by conjugate gradient technique. From this operation optimization study, it is concluded as follows :

(i) More water be drawn from Bhakra reservoir to meet irrigation release targets at Ropar and Harike headworks (Fig. 3.3) for optimal power generation instead of spilling from Pong reservoir. This is contrary to the present operation procedure being followed by regulating engineers indicated in Table 4.1 and 4.2. This results into lowering Bhakra reservoir levels, however, it is found from the studies that final levels are very near to full reservoir levels.

(ii) Operation optimization studies 1, 2 and 3 have shown increase in annual average power generation by 37.7, 66.3 and 5.1 MW respectively.

(iii) This extra water withdrawal from Bhakra reservoir would also ultimately increase the generation in the downstream under construction power plant at Anandpur Sahib.

(iv) Finally, the developed optimization technique would be a valuable tool to the operation planners of this system or any other multireservoir system especially for taking fortnightly or monthly decisions for water releases for irrigation and power generation objectives. These findings would effect savings in water, increase in energy and peak capabilities.

For the short range study, a mathematical technique and Computer programmes have been developed to obtain optimal discharges and schedules for Bhakra Power Plants without any conflicts with the existing operational strategies and under the varying conditions of tail race and reservoir levels, load, spinning reserve and Nangal Fertilizer Factory loads.

Long hand calculations would be impracticable for optimum scheduling. The programming technique would help in conservation of water from 0.5 to 2 percent and to optimize generation from hydel stations and as such would be valuable contribution to power industry. The programmes could be further modified for scheduling the generation of hydro plants of the entire BBMB system. Central Board of Irrigation and Power has brought out a technical report from this research study and being followed by the field engineers.

Hourly case oriented study has been conducted for preparing optimal daily schedules of regulation for newly constructed Beas Satluj Link Balancing Reservoir. Generalised iterative optimization programme has been developed for framing schedules of regulation and will form a sub-routine to Bhakra-Beas system medium range study. The study has achieved the objectives of maximum power generation and water transfer, maintaining high levels and bringing the balancing reservoir to full level at the end of day and limiting operation of control structure at head race tunnel and variation of channel flows in Tables 6.3, 6.4 and 6.5. Compared results with so far operation records are encouraging and will improve the operation. It is recommended to use optimization study schedule of regulation given in Table 6.6.

7.2 Recommendations for Future Work

The study has exposed other problem areas where further work could be initiated.

(i) Streamflow forecasting models could be used with stochastic optimization techniques to cover the uncertainty in the inflows.

(ii) Unit Commitment and generation scheduling study may be extended to include other power plants of the entire Northern grid through the application of microprocessor control system. This study can include load flow model for keeping voltage and frequency of system in limits.

(iii) Conjunctive utilization of surface water and ground water for Bhakra-Beas system can be studied by extending the developed system model.

(iv) Integrated Planning study of Bhakra-Beas system can include hourly model of Beas Satluj Link Project and Thein Power Plant under construction on river Ravi.

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INDEX FOR ABBREVIATIONS IN REFERENCES

AIEE	American Institute of Electrical Engineers
AWRA	American Water Resources Association
ASCE	American Society of Civil Engineers
BBMB	Bhakra Beas Management Board, Nangal Township
CBI & P	Central Board of Irrigation and Power
CEA	Central Electricity Authority
CSIR	Council of Scientific and Industrial Research
IE	Institution of Engineers
IEE	Institution of Electrical Engineers
IEEE	Institution of Electrical and Electronic Engineers
IS	Indian Standard
JIE(I)	Journal of Institution of Engineers(India)
N	Number
PAS	Power Apparatus and Systems
Vol.	Volume
WRB	Water Resources Bulletin
WRR	Water Resources Research

APPENDIX 1

BARD ALGORITHM FOR CURVE FITTING

The method is based on the linearization of the polynomial expression. Linearization of expression $P_G = A_k Q^B$ (1.1) by Taylor's Series, we have :

$$P_{G_j} = (P_{G_j})_o + \left(\frac{\partial P_{G_j}}{\partial AK} \right)_o \Delta AK + \left(\frac{\partial P_{G_j}}{\partial B} \right)_o \Delta B \qquad (1.2)$$

where

$\Delta AK = (AK = AK^o)$

$\Delta B = (B - B^o)$

and AK^o and B^o are the initial estimate of quantities AK and B. $(\quad)_o$ represent the value of the expression given within the bracket evaluated at AK^o and B^o.

Let $P^*_{G_j}$ and Q^*_j (j = 1,2, ..., N) are data prints on the plant performance curve for a particular head. A least square objective function is formulated as :

$$\underset{AK,B}{\text{Minimize}} \quad F = \sum_{j=1}^{N} (P^*_{G_j} - P_{G_j}) \qquad (1.3)$$

Replacing P_{G_j} in (1.3) by (1.2) we get :

$$\underset{AK,B}{\text{Minimize}} \quad F = \sum_{j=1}^{N} \left[P^*_{G_j} - (P_{G_j})_o - \left(\frac{\partial P_{G_j}}{\partial AK} \right)_o \Delta AK - \left(\frac{\partial P_{G_j}}{\partial B} \right)_o \Delta B \right]^2 \qquad (1.4)$$

The necessary conditions for optimality is :

$$\frac{\partial F}{\partial AK} = 0 \qquad (1.5)$$

$$\frac{\partial F}{\partial B} = 0 \qquad (1.6)$$

From optimality equations (1.5) and (1.6), we get :

$$\begin{bmatrix} \frac{\partial P_{G_1}}{\partial AK} & \frac{\partial P_{G_1}}{\partial B} \\ \frac{\partial P_{G_2}}{\partial AK} & \frac{\partial P_{G_2}}{\partial B} \\ \vdots & \vdots \\ \frac{\partial P_{G_N}}{\partial AK} & \frac{\partial P_{G_N}}{\partial B} \end{bmatrix} \begin{bmatrix} AK-AK^o \\ B-B^o \end{bmatrix} = \begin{bmatrix} P^*_{G_1} - (P_{G_1})_o \\ P^*_{G_2} - (P_{G_2})_o \\ \vdots \\ P^*_{G_N} - (P_{G_N})_o \end{bmatrix} \qquad (1.7)$$

which can be written in compact forms :

$$[A] \begin{bmatrix} \Delta AK \\ \Delta B \end{bmatrix} = [P^*_G - (P_G)_o] \qquad (1.8)$$

Normalizing above set of linear equation :

$$[A^t A] \begin{bmatrix} \Delta AK \\ \Delta B \end{bmatrix} = A^t [P^*_G - (P_G)_o] \qquad (1.9)$$

These equations can be solved to find the values of ΔAK and ΔB. The stepwise procedure can be explained as follows :

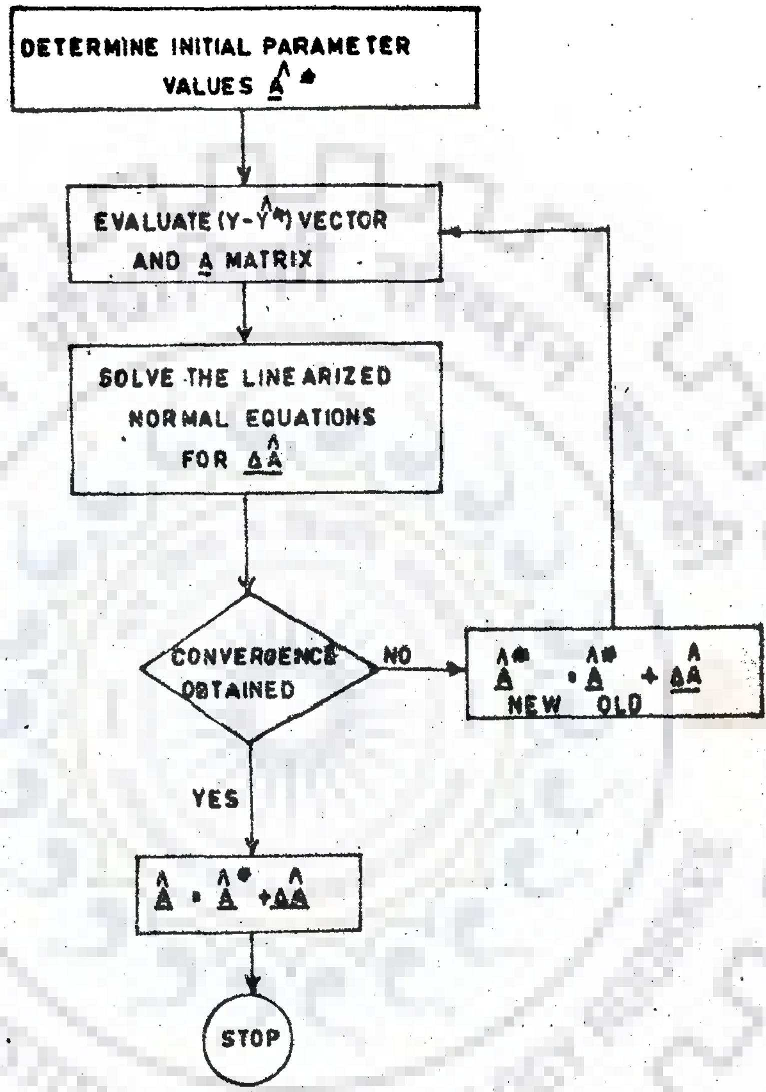
1. Read $P^*_{G_j}$ and $Q^*_{G_j}$ ($j = 1 \ldots n$) from plant performance curve.

2. Make an initial estimate of quantities AK^o and B^o
3. Calculate vector ($P^*_{G_j}$ - $(P_G)_o$ and matrix A.
4. Solve a system of linear equation (1.9) to calculate ΔAK and ΔB.
5. Check if $|AK| \leq$ tol and $|\Delta B| \leq$ tol, stop, otherwise go to next step.
6. Calculate new values of AK and B from

   $AK = AK^o + \Delta AK$

   $B = B^o + \Delta B$

   Replace AK^o by AK and B^o by B and go to step 3.



APPENDIX II – GAUSS NEWTON (BARD ALGORITHM) LOGIC DIAGRAM FOR CURVE FITTING.

APPENDIX III

PONG RESERVOIR CAPACITY IN CUSEC DAYS AT DIFFERENT ELEVATIONS

Elevation in feet	CAPACITY IN CUSEC DAYS				
	(0)	(2)	(4)	(6)	(8)
1260	526342	543988	564154	586841	609529
1270	631712	654399	677086	699773	722460
1280	746156	774389	802117	830350	858079
1290	886312	914041	942274	970507	1004790
1300	1039072	1073355	1107638	1141921	1176204
1310	1210487	1244769	1283085	1322410	1361230
1320	1400555	1439879	1479203	1518528	1557348
1330	1600706	1646080	1690950	1736325	1781699
1340	1827073	1872448	1917318	1965213	2016133
1350	2066549	2117469	2168389	2218805	2269725
1360	2320645	2372574	2429040	2485505	2541971
1370	2598437	2654903	2711369	2767835	2824300
1380	2884800	2945299	3006302	3066801	3127300
1390	3187799	3248298	3309302	3374338	3440383
1400	3506428	3572473	3638518	3704563	3770608
1410	3836652				

Source : Beas Dam Talwara

APPENDIX IV

BHAKRA RESERVOIR CAPACITY IN CUSEC DAYS AT DIFFERENT ELEVATIONS

Elevation in feet	CAPACITY IN CUSEC DAYS (0)	(2)	(4)	(6)	(8)
1400	518578	528349	538119	547890	557660
1410	567431	577202	586972	596743	606513
1420	616284	627093	637902	648712	659521
1430	670320	681149	691969	702787	713607
1440	724427	736274	748122	759970	771817
1450	783665	795513	807361	819208	831056
1460	842904	856395	869886	883378	896869
1470	910360	923861	937363	950864	964366
1480	977867	993425	1008984	1024542	1040101
1490	1055659	1071217	1086776	1102334	1117893
1500	1133451	1150986	1168520	1186055	1203589
1510	1221124	1238669	1256214	1273758	1291303
1520	1308848	1328853	1348858	1368863	1388868
1530	1408873	1428888	1448903	1468919	1488934
1540	1508949	1531132	1553315	1575498	1597681
1550	1619864	1642047	1664230	1686413	1708596
1560	1730779	1755231	1779683	1804134	1828586
1570	1853038	1877490	1901941	1926393	1950844
1580	1975296	2002228	2029160	2056093	2083025
1590	2109917	2136889	2163821	2190754	2217686
1600	2244618	2274303	2303968	2333673	2363358
1610	2393043	2422728	2452413	2482097	2511782
1620	25541467	2574147	2606826	2639506	2672185
1630	2704865	2737555	2770245	2802934	2835624
1640	2868314	2904139	2939965	2975790	3011616
1650	3047441	3083257	3119072	3154888	3190703
1660	3226519	3265440	3304361	3343282	3382203
1670	3421124	3460045	3498966	3537888	3576809
1680	3615730	3657928	3700126	3741427	3781830
1690	3822233	3865198	3908162	3951127	3994091
1700	4037056				

Source : BBMB

APPENDIX- V

PERFORMANCE CURVES SAFE ZONE OPERATING DATA

BHAKRA LEFT BANK POWER PLANT

HEAD - 300'

MW	Q
35	1685.0
40	1935.0
45	2100.0
50	2280.0
55	2470.0
60	2655.0
65	2875.0

HEAD- 320'

MW	Q
40	1812.5
45	2000.0
50	2145.0
55	2312.5
60	2500.0
65	2720.0
70	2875.00
75	3095.00

HEAD-340'

50	2025.0
55	2195.0
60	2350.0
65	2505.0
70	2680.0
75	2875.0
80	3050.0
85	3290.0

HEAD -360'

60	2255.0
65	2400.0
70	2565.0
75	2720.0
80	2875.0
85	3060.0
90	3230.0

HEAD-380'

65	2355.0
70	2475.0
75	2625.0

HEAD-400'

70	2355.0
75	2475.0
80	2615.0

MW	Q
80	2750.0
85	2900.00
90	3055.0
95	3250.0
100	3380.0

MW	Q
85	2780.0
90	2890.0
95	3075.0
100	3235.0

HEAD -420'

70	2250.0
75	2375.0
80	2500.0
85	2637.0
90	2765.0
95	2910.0
100	3980.0

HEAD-440'

80	2425.0
85	2550.0
90	2690.0
95	2835.0
100	2975,0

HEAD -460'

90	2580.0
95	2745.0
100	2875.0

HEAD-480'

90	2535.0
95	2640.0
100	2780.0

HEAD- 500'

90	2415.0
95	2545,0
100	2650.0

MW	Q
110	3805.0
115	3950.0
120	4125.0

MW	Q
115	3805.0
120	3940.0

HEAD - 420'

90	2930.0
95	3065.0
100	3230.0
105	3375.0
110	3505.0
115	3655.0
120	3780.0

HEAD - 440'

95	2965.0
100	3078.0
105	3230.0
110	3358.0
115	3500.0
120	3625.0

HEAD - 460'

100	3025.0
105	3150.0
110	3270.0
115	3392.0
120	3500.0

HEAD - 480'

100	2895.0
105	3040.0
110	3140.0
115	3260.0
120	3375.0

HEAD - 500'

100	2865.0
105	2970.0
110	3095.0
115	3187.5

APPENDIX VI

BEAS-SATLUJ LINK COMPONENT DETAILS

1. PANDOH RESERVOIR

Max. reservoir level	EL 896.42 m
Normal reservoir level	EL 883.92 m
Min. reservoir level	EL 883.92 m
Gross storage capacity	4100 hectare meters
Live storage capacity	3243.60 hectare meters

2. PANDOH BAGGI TUNNEL

Diameter	7.62 m
Length	13.10 Km
Capacity	254.85 m^3/s

3. BAGGI CONTROL WORKS

No. of conduits	4
No. of gates in each conduit	2

4. SUNDERNAGAR HYDEL CHANNEL

F.S. Discharge at head	240.69 m^3/s
F.S. Discharge at tail	212.38 m^3/s
Length	11.80 Km

5. SUNDERNAGAR BALANCING RESERVOIR

Max. height of embankment	21.34 m
Length of reservoir	2134 m
Max. width of reservoir	457.20 m
Max. reservoir level	EL 842.47 m
Top of embankment	EL 844.90 m
Capacity of Syphon Escape	328.51 m^3

6. SUNDERNAGAR SATLUJ TUNNEL

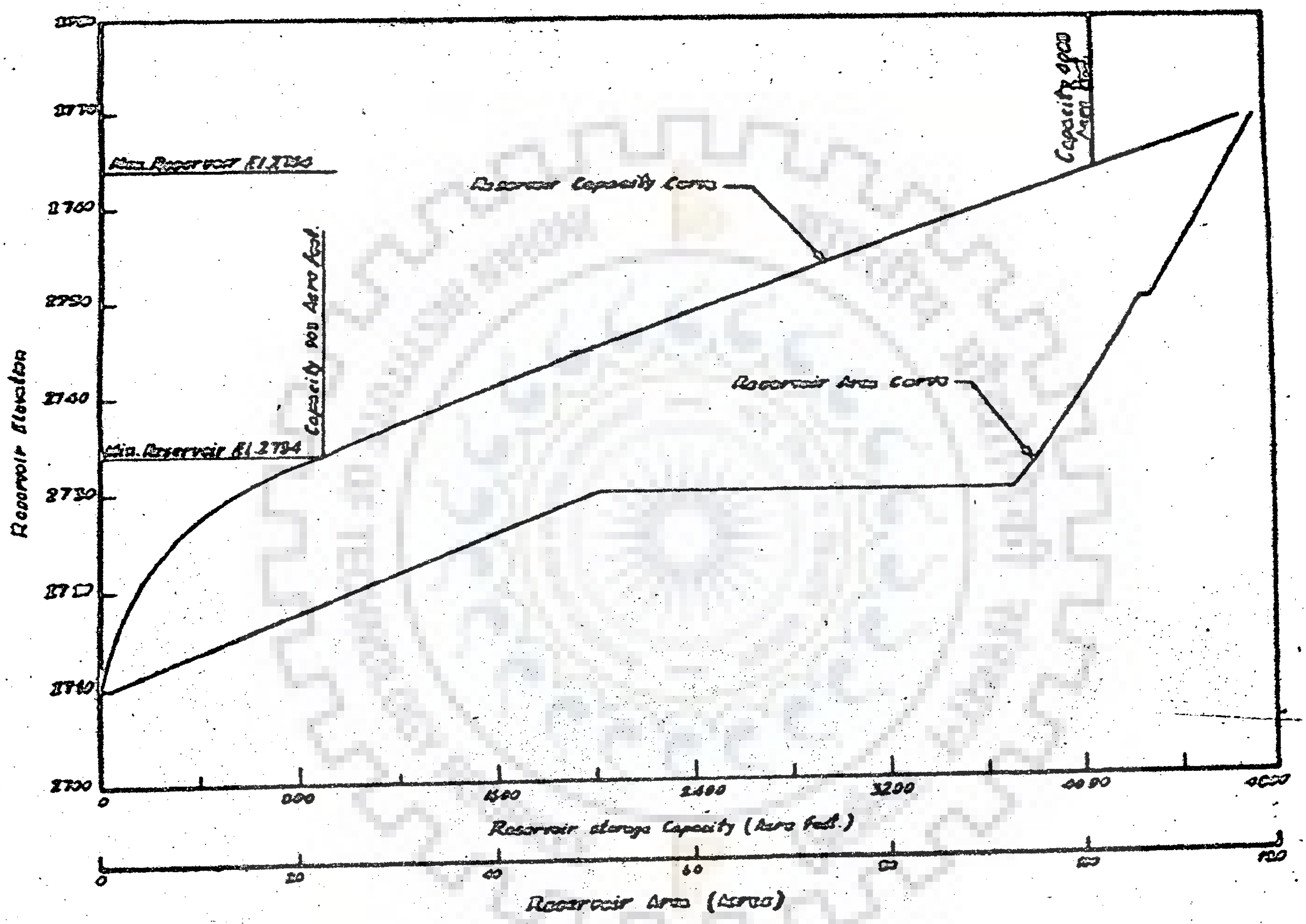
Diameter	8.53 m
Length	12.38 km
Capacity	403.52 m^3/s

7. BY-PASS TUNNEL AND CHUTE

Diameter of tunnel	7.71 m
Length of tunnel	296.8 m
Length of chute	533.40 m

8. DEHAR POWER PLANT

No. of units in first stage	4
No. of units in near future	2
Initial installed capacity	660 MW
Ultimate installed capacity	990 MW
Design head	320 m
No. of penstock headers	3



APPENDIX VII B.R. ELEVATION Vs. AREA AND STORAGE CURVES

Period		Beas Dependable Inflows (cumecs)	Beas Satluj Diversions (cumecs)	Inflow-Outflow Difference (cumecs)	Difference in (hm)	Pandoh Reservoir Pondage Variation (hm)
June	(1-10)	276.00	212.38	63.62	5377.11	3243.64
	(11-20)	340.99	212.38	128.61	10756.94	3243.64
	(21-30)	412.01	212.38	199.63	16871.01	3243.64
July	(1-10)	505.00	212.38	292.62	24729.21	3243.64
	(11-20)	575.00	212.38	362.62	30644.82	3243.64
	(21-31)	588.00	212.38	375.62	31743.26	3243.64
August	(1-10)	618.02	212.38	405.64	34279.85	3243.64
	(11-20)	657.01	212.38	444.63	37575.04	3243.64
	(21-31)	540.99	212.38	328.61	27770.86	3243.64
September	(1-10)	426.00	212.38	213.62	18052.91	3243.64
	(11-20)	311.00	212.38	96.62	8334.82	3243.64
	(21-30)	244.01	212.38	31.63	2673.02	3243.64
October	(1-10)	174.99	212.38	-37.38	-3158.77	84.87
	(11-20)	133.99	113.28	20.71	1751.71	1836.58
	(21-31)	110.29	113.28	- 2.99	- 275.20	1561.38
November	(1-10)	88.01	70.79	17.22	1454.92	3016.30
	(11-20)	82.01	70.79	11.22	950.47	3243.64
	(21-30)	76.00	70.79	6.79	440.36	3243.64
December	(1-10)	69.01	70.79	- 1.78	-150.73	3092.91
	(11-20)	64.99	70.79	- 5.80	-490.57	2602.34
	(21-31)	60.00	70.79	-10.79	-911.68	1690.66
January	(1-10)	59.01	70.79	-11.78	-997.91	692.75
	(11-20)	57.00	56.63	0.37	31.08	723.83
	(20-31)	54.99	56.63	- 1.64	-138.77	585.06
February	(1-10)	60.00	56.63	3.37	284.82	869.88
	(11-20)	60.00	56.63	3.37	284.82	1154.70
	(21-28)	62.01	56.63	5.38	454.67	1609.37
March	(1-10)	69.00	70.79	- 1.79	- 88.44	1520.93
	(11-20)	89.99	70.79	19.20	1622.40	3143.33
	(21-31)	102.00	113.28	-11.28	-952.39	2190.94
April	(1-10)	121.99	113.28	8.71	737.02	2927.96
	(11-20)	145.01	155.74	-10.73	- 897.38	2030.58
	(21-30)	172.98	184.06	-11.08	- 935.62	1094.96
May	(1-10)	181.99	184.06	- 2.07	- 180.34	914.62
	(11-20)	206.99	212.38	- 5.39	- 454.67	459.95
	(21-31)	244.00	212.38	31.62	2673.02	3132.97

VITA

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Candidate for the Degree of
Doctor of Philosophy

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