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Planning and Analysis of Optimum Operation of Upper Tamakoshi Hydroelectric Project

Ramesh Adhikari [a], Sanjaya Neupane [b], Bhakta Bahadur Ale [c]

[a,b,c] *Pulchowk Campus, IOE, TU, Nepal*
Corresponding Email: [a] rames046@gmail.com, [b] sanjaya@pcampus.edu.np, [c] bhaktaale@yahoo.com

Abstract
This paper deals with modelling of Upper Tamakoshi Hydroelectric Project for the optimization of unit performance by economic distribution of available discharge of water for production of maximum power output and optimization of reservoir for daily operation to meet the load at different time frame in a day. First, optimization is applied to determine maximum power generation that can be achieved with proper discharge distribution among units. Second, optimization of reservoir is done to meet the load demand of Integrated Nepal Power System at different time throughout a day during dry season so as to manage power import from India in a proper way.

Keywords
Reservoir Optimization, Discharge Distribution, Power Optimization

1. Introduction

Electricity demand in Nepal is on an increasing trend with about 78% of total population having electric supply [1]. With the increasing growth rate of customers availing electricity services of Nepal Electricity Authority (NEA), power and energy demand is also increasing accordingly. The total available energy in Integrated Nepal Power System (INPS) in 2018/19 was 7551.23 GWh which is an increase by 6.99% over previous year [1]. Out of total energy supply, NEA's generation contributed 33.75%, generation of Independent Power Producer (IPPs) contributed 29% whereas the remaining 37.25% of energy was imported from India [1].

Even though peak power demand and energy demand has continuously increased, increase in electricity generation is not in par with demand. A large chunk of demand is met with imported energy from India. Total installed capacity of INPS grid reached to 1173.48 MW in 2018/19 only, which is low compared to the peak demand of 1320.28 MW [1]. Peak demand is highest in dry season when generation from hydropower plants is at their lowest.

System load curve during dry season shows that energy generation in Nepal is low with respect to demand and a large chunk of demand is met by the imported energy. During peak hours, the share of imported energy is more than fifty percent [1].

It is of importance that new hydropower plants have to be timely constructed to meet growing electricity demand and to decrease dependency on imported energy. Since development of hydropower plants takes long time, other avenues should be explored as well. Though the increasing trend of annual peak demand reduced in 2018/19, further measures have to be implemented to meet it through local generation. Optimum operation of existing or upcoming large hydropower plants especially during dry season can provide a boost in that direction.

This research focuses on the optimized operation of Upper Tamakoshi Hydroelectric Project (UTKHEP) which is a Peaking Run of River (PROR) plant. The main objective of the research is to optimize unit generation and daily energy generation of Upper Tamakoshi Hydroelectric Project (UTKHEP).

Optimization is a mathematical technique for finding maximum or minimum value of a function of several variables subject to a set of constraints [2]. Optimization of hydropower is a way of unit commitment where certain units are preferred over others for maximum generation of power [3].

Hydropower plants with peaking reservoir or pondage have a facility for storage of limited quantity for a specific period of time. Such PROR plants store available water during off-peak periods to utilize it during peak hours. Energy generation in such plants vary throughout a day, unlike Run of River (ROR) plants. Formulation of optimization problem in such plants is more complicated than ROR plants, as the capacity of reservoir comes into play. This must be dealt with addition of time factor. This creates additional constraints of reservoir inflow, reservoir capacity and maintaining reservoir level within allowable minimum and maximum limit over a specific period of time.

Study of operation optimization of power by distributing discharge and committing unit at Devighat hydropower plant has shown that enhancement in generation up to 2.62% is achievable [4]. Operational optimization of Middle Marsyangdi hydropower plant shows that generation gain up to 7.20% can be achieved with same use of discharge [5]. Study of optimization of Hoa Binh river in Vietnam has shown that improvement in hydropower generation by 2.2% can be achieved [6]. The study performed on Xiluodu 912,600 MW) and Xiangjiaba (6,000 MW) cascaded hydropower stations located in Jisha river in China by short term hydropower generation scheduling using binary coded bee colony optimization algorithm has shown that water saving of 1.36% of actual water consumption can be achieved under same load conditions and river inflow [7].

Brief Introduction of UTKHEP

UTKHEP is a daily PROR project of installed capacity 456 MW (6*76 MW) located at Bigu Rural Municipality of Dolakha district. It has a gross head of 822 m and design discharge of $66m^3/s$ with live storage volume capacity of $0.9Mm^3$ sufficient for minimum four hours daily peaking operation in the driest month.

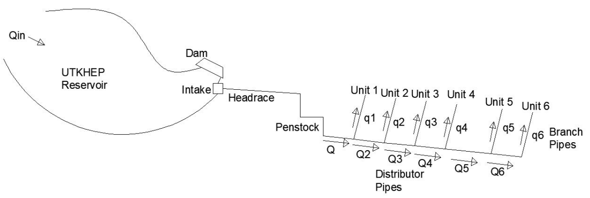

Figure 1: Schematic Diagram of UTKHEP

2. Optimization Model Development

The dispatch of power in multi-unit generating plants can be in such way that total power is generated proportionally by all available units. The power delivered by plant is equally divided among available units. This would be true if characteristics and operating efficiency of all units were same. However, this is not the case in operating conditions as there are a lot of factors governing efficiency and operation of each unit. The main reason is that energy losses occurring in each unit is different because of arrangement of the units.

The penstock head loss considered in the research is major head occurring in headrace tunnel and penstock conduit pipes. Head loss is calculated using Darcy-Weisbach equation for varying values of discharge and equations are formulated for head loss occurring at different sections using regression analysis. The equation for penstock head loss (HL_p) in relation to total discharge (Q) is

$$HL_p = 0.0041027 * Q^2 + 0.1278269 * Q \quad (1)$$

Penstock head loss is the head loss up to first branch pipe. Head loss for different units depends upon their respective branch pipe head loss and head loss taking place in distributor pipes. Distributor pipes of the project is decreasing in size with distributor pipe 2 being the largest and distributor pipe 6 being the smallest. Distributor pipe 2 is designed for maximum discharge of $55m^3/s$, distributor pipe 3 is designed for maximum discharge of $44m^3/s$ and so on. The equations for distributor head loss in relation to distributor discharge (Q_n) are as follows:

$$HL_{d2} = 0.0001336 * Q_2^2 \quad (2)$$

$$HL_{d3} = 0.0002389 * Q_3^2 \quad (3)$$

$$HL_{d4} = 0.005213 * Q_4^2 \quad (4)$$

$$HL_{d5} = 0.0033198 * Q_5^2 \quad (5)$$

$$HL_{d6} = 0.0073757 * Q_6^2 \quad (6)$$

The branch pipes of all units are similar in construction and the equation for branch pipe head loss in relation to unit discharge(q_n) is

$$HL_{bn} = 0.0014541 * q_n^2 \quad (7)$$

Thus, the total head loss for units 1 to 6 would be respectively

$$HL_1 = HL_p + HL_{b1} \quad (8)$$

$$HL_2 = HL_p + HL_{d2} + HL_{b2} \quad (9)$$

$$HL_3 = HL_p + HL_{d2} + HL_{d3} + HL_{b3} \quad (10)$$

$$HL_4 = HL_p + HL_{d2} + HL_{d3} + HL_{d4} + HL_{b4} \quad (11)$$

$$HL_5 = HL_p + HL_{d2} + HL_{d3} + HL_{d4} + HL_{d5} + HL_{b5} \quad (12)$$

$$HL_6 = HL_p + HL_{d2} + HL_{d3} + HL_{d4} + HL_{d5} + HL_{d6} + HL_{b6} \quad (13)$$

The equation of power generation for each unit is given by

$$P_n = 9.81 * H_n * q_n * \eta \quad (14)$$

where,
H_n = net head for each unit, m
q_n = discharge available at each unit, m^3/s
η = efficiency of each unit

The net head for respective unit would be the difference between gross head and head loss for that unit. The gross head of project varies for a total of 4m ranging from 818 m to 822 m. The total design discharge is $66m^3/s$ whereas the maximum unit discharge is $11m^3/s$. Efficiency of each unit is the product of generator and turbine efficiency which depends upon respective unit discharge.

Power generated by each unit is calculated and total power generated by plant is the sum of power delivered by each unit.

2.1 Optimization Model for Unit Power Generation

The optimization model is maximization of total power generation at a given value of gross head and discharge. The head and discharge of plant vary and optimal distribution of total discharge to available units for maximum power generation is the objective function for optimal unit power generation.

The objective function is

Maximize Total Power = P_1 + P_2 + P_3 + P_4 + P_5 + P_6
where,
P_1, P_2, P_3, P_4, P_5, P_6 are the power generated by units 1, 2, 3, 4, 5 and 6 respectively.

The constraints are

a) Power delivered by each unit should be positive
$P_1, P_2, P_3, P_4, P_5, P_6 \geq 0$

b) Minimum unit discharge should be $3.3m^3/s$ as it is the minimum discharge required by turbine for power generation. The maximum unit discharge should be $11m^3/s$.
$3.3m^3/s \leq$ Unit Discharge (q_n) $\leq 11m^3/s$

2.2 Optimization Model for Reservoir Operation

The objective function of the model is maximization of total hydropower generation over a day.

The objective function is

Maximize Power = Sum (P_t) for t = 1, 2, 3.......T
where,
P_t = Power generation at time t
T = time period, i.e. 24-hour period

The constraints are

a) Reservoir Volume
The reservoir storage volume capacity should be within prescribed limits of minimum and maximum storage.
$0 \leq S_t \leq 0.9Mm^3$

The volume of reservoir depends upon water inflow into reservoir, water outflow from reservoir and time duration and is given by the following equation:
$S_{t+1} = S_t + (Q_{in} - Q_{out}) * t$
where,
S_{t+1} and S_t are storage volume of reservoir at ending and starting period of time t respectively.

b) Reservoir Capacity Balance

The storage volume of the reservoir at starting period and ending period of time is same.

$S_1 = S_{T+1}$

c) Water Outflow

The maximum allowable outflow should be less than discharge limit to produce maximum power whereas the minimum water outflow should be the minimum allowable discharge through turbine.

$Q_{min} \leq Q \leq Q_{max}$

d) Power Generation

The limit for minimum and maximum power generation can be fixed at any time instant. Also, the minimum and maximum power required to be produced at any time instant can also be fixed.

e) Imported Load

The imported load from India is varying throughout the day with high import during peak hours and comparatively less import during off-peak hours. The optimization is done in such a way that import would have a constant value throughout day with additional import load to be minimized such that the load import curve is flattened.

3. Results and Discussions

3.1 Power Optimization

The total available discharge is to be distributed among six units such that the total power generation would be maximum.

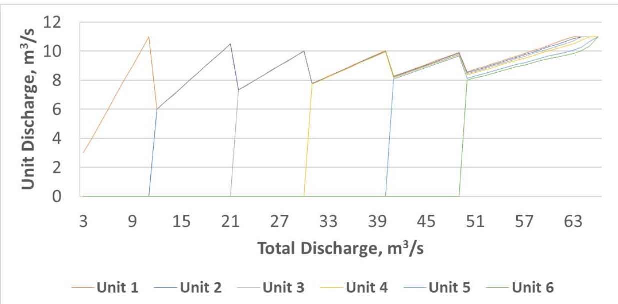

Figure 2: Optimal Discharge Distribution between Units

It is observed that priority is given to Unit 1 till total discharge is $11m^3/s$ because penstock head loss is low for Unit 1 as compared to other units because of shorter hydraulic path. The power generation from Unit 1 is maximum at this point. After discharge exceeds $11m^3/s$, it is distributed between Unit 1 and Unit 2 with both units generating power. The third unit is operated when the total discharge exceeds $21m^3/s$ where it is distributed among three units such that total power generated by the plant is maximum. This distribution continues till discharge exceeds $49m^3/s$ where discharge is distributed among all six units. It is noteworthy that when all six units are running, discharge is not distributed equally among them. Unit 1 is given more discharge followed by unit 2 and so on to maximize total power generation. Such distribution of discharge would be a key decision making tool for plant operators.

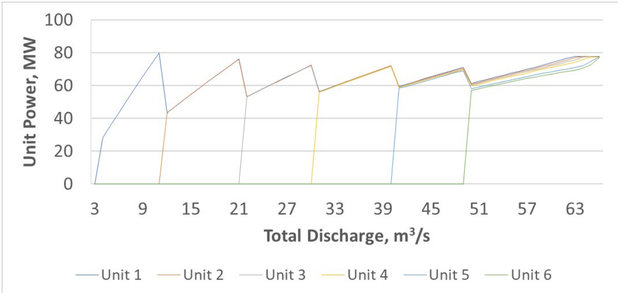

Figure 3: Optimal Unit Generation for gross head 819 m

From figure 3 showing optimal power generation, it is found that operating characteristics of different units and their operating efficiency plays a vital role in the formulation of optimal generation model.

The comparison of the optimization model of power generation is performed with equal distribution of total discharge between available units. The total power generation from optimization model for each value of discharge is compared with total power generation from model developed for equal distribution of discharge among available units.

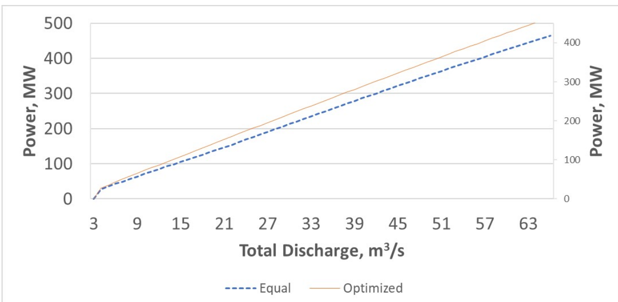

Figure 4: Power Generation - Optimal vs Equal Discharge

Figure 4 shows total power generation when units are running in optimized condition and when units are running during equal distribution of discharge between them.

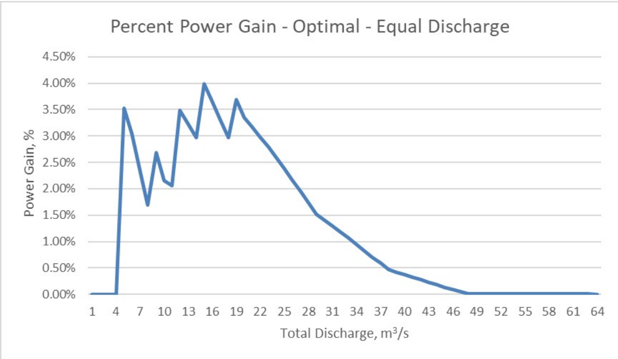

Figure 5: Power Gain - Optimal - Equal Discharge

Figure 5 shows percentage power gain achieved from optimal distribution of discharge as compared to equal distribution. For high value of discharge, variation in power output from both modes of discharge distribution is quite low. But for medium and low discharge, power output from optimized distribution is significantly high. This indicates that for medium and low flow condition, practice of equal distribution is not an effective way of power generation. After discharge of $41m^3/s$, optimized operation has five units operating, so unit commitment is best applicable below this range of discharge.

3.2 Reservoir Optimization

Daily live reservoir capacity of UTKHEP reservoir is $0.9Mm^3$ that can be utilized within a day. The reservoir filling time for different months in a year is different as it depends upon the inflow into reservoir. The minimum inflow is during March where discharge is $14.1m^3/s$. The reservoir is to be used such that maximum power can be generated from it. Another way of using reservoir is to utilize it to meet daily load curve of INPS. The daily load curve of INPS has two peaks – one in morning and another in evening, when demand is high.

3.2.1 Month of March

Total Live Reservoir Capacity = $0.9Mm^3$
Inflow = $14.1m^3/s$

Time required for reservoir filling
=$0.9Mm^3$ / $14.1m^3/s$
= 17.73 hrs

The reservoir will fill up completely in 17.73 hours.

Maximum possible outflow through turbines = $66m^3/s$

Maximum time for peak load operation
=$0.9Mm^3$ / (66-14.1) m^3/s
= 4.82 hrs

The plant can be operated as a peaking plant for 4.82 hours.

The comparison is done for daily generation between ROR, PROR and import optimization of plant. The daily load curve considered is of 03 March 2020. Peak hour is considered for two hours in morning time from 07.00-09.00 and four hours in evening time from 16.00-20.00 when demand is above 990 MW.

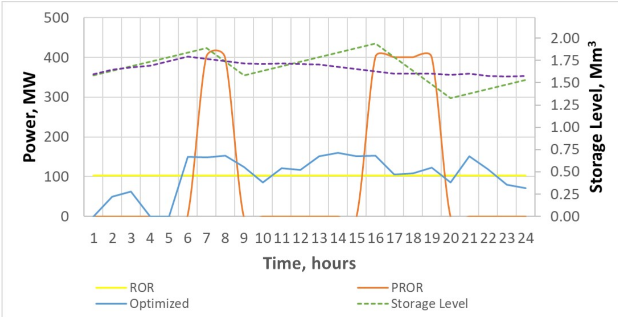

Figure 6: Different Modes of Generation - March

Mode of Generation	Daily Energy Generation
ROR	2467.223 MWh
PROR	2407.047 MWh
Import Optimization	2464.823 MWh

When the plant is operated in import optimization mode, minimum import from India is fixed at 300 MW, i.e. 300 MW is imported from India throughout the day. Optimization is performed for additional power import from India. Hourly generation of UTKHEP is varied throughout the day as compared to ROR or PROR generation. During time of maximum power import from India, plant is generating more power and during time of minimum import, plant is shut down so that import load curve is flattened.

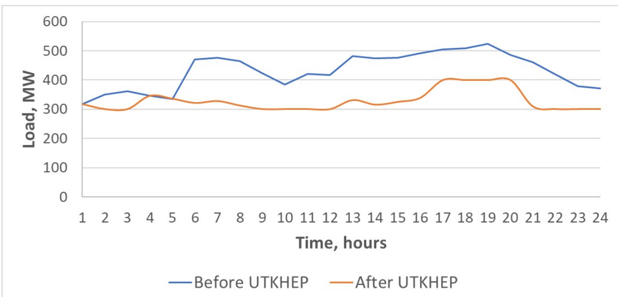

Figure 7: Comparison of Imported Load - March

3.2.2 Month of January

Total Live Reservoir Capacity = $0.9Mm^3$
Inflow = $16m^3/s$

Time required for reservoir filling
= $0.9Mm^3$ / $16m^3/s$
= 15.63 hrs

The reservoir will fill up completely in 15.63 hours.

Maximum time for peak load operation
=$0.9Mm^3$ / (66-16) m^3/s
= 5 hrs

The plant can be operated as a peaking plant for 5 hours.

The comparison is done for daily generation between ROR, PROR and import optimization of plant. The daily load curve considered is of 27 January 2020. Peak hour is considered for three hours in the morning time from 08.00-11.00 and three hours in the evening time from 18.00-21.00 when the load is above 1175 MW.

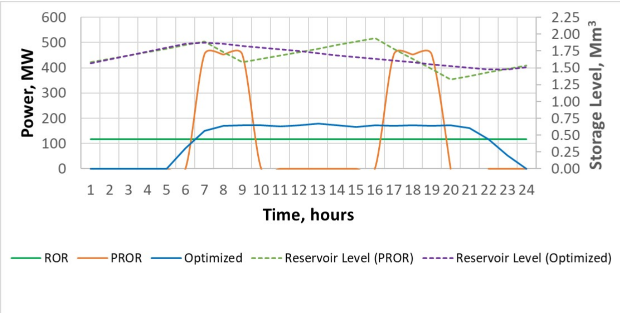

Figure 8: Different Modes of Generation - January

Mode of Generation	Daily Energy Generation
ROR	2800.004 MWh
PROR	2714.947 MWh
Import Optimization	2794.016 MWh

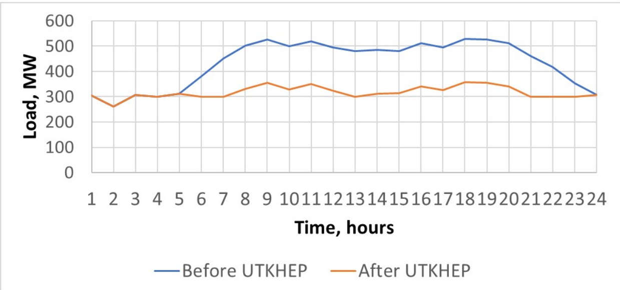

Figure 9: Comparison of imported Load - January

Power generation from UTKHEP is such that it produces almost constant power from early morning to midnight and does not produce power at other times. With such generation, import load curve from India is flattened. When power import from India is below 300 MW, UTKHEP does not generate electricity.

3.2.3 Month of July

Even during wet season when discharge in rivers is maximum and all power plants are producing maximum power, power is imported from India. This trend of power import from India seems necessary to meet the demand until UTKHEP is connected to INPS. UTKHEP would produce maximum power throughout day during wet season and once UTKHEP is connected to the national grid, it would result in total available supply power to be greater than demand.The daily load curve considered is of 08 July 2019.

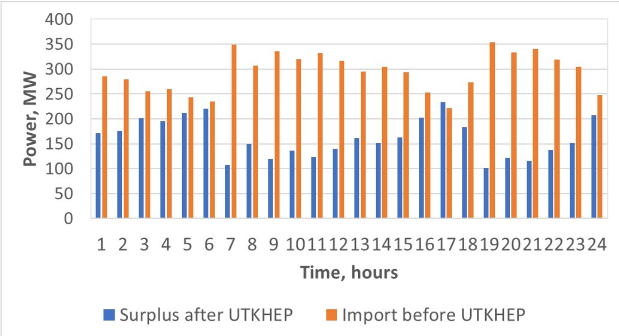

Figure 10: Comparison of Import and Surplus Power

Energy import from India before UTKHEP is all around the day with maximum import of around 350 MW in peak time at morning and evening. After the operation of UTKHEP in full swing, local generation of electricity would be greater than the current demand throughout the day. Power in INPS is excessive all day with maximum surplus reaching around 230 MW.

Effective measures have to be implemented for the consumption of surplus power. Following are some measures that can be implemented for utilization of surplus power:
a) Energy Banking with India
b) Energy Trading with Bangladesh
c) Seasonal Tariff
d) Seasonal Industrial Consumption

4. Conclusion

The output from hydro power plant is a function of net head, available discharge and unit efficiency. Different units in a multi-unit hydropower plant do not have same operating efficiency. The head loss of different units is different because of difference in hydraulic path. Head loss is minimum for nearest unit and maximum for furthest unit even for same value of discharge as water has to travel more.

The power optimization allows for the distribution of discharge such that Unit 1 is operated for all conditions of total discharge. Unit 2 is started with increase in total discharge with discharge distributed between unit 1 and 2. This process is continued up to unit 6 is turned on. After all units are operating, more discharge is allowed to unit 1 than others until maximum discharge where it is distributed equally.

It shows that generation gain up to 4 % can be achieved with optimal distribution of discharge when compared to equal distribution of discharge.

The plant can be operated as a peaking plant up to 4.82 hours in March and 5 hours in January. The plant can be run in ROR mode with constant generation through the day, PROR mode with generation during the peak time only or making import load constant with reservoir optimization. The import load curve in the dry season can be flattened to a certain extent with maintaining minimum import and optimizing the additional import with UTKHEP.

With UTKHEP generating maximum power during wet season, power import would not be required and total local generation of power would be excessive than power demand. This would result in surplus generation throughout day which needs to be effectively managed.

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