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Plant Operation Optimization- A Case Study of Middle Marsyangdi Hydropower Station

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Abstract

Operation optimization of an existing hydropower plant incorporates optimal unit commitment and economic distribution of available water discharge. It includes using all available discharge to produce maximum output power and to meet required power demand with lowest possible discharge consumption. In this paper, non-linear generalized reduced gradient method is used to solve the optimization problem for Middle Marsyangdi Hydropower Station (MMHPS). Individual unit performance is determined based on existing operational data. The solution of the optimization model is applied to determine optimal generation and discharge requirement. The results demonstrate that generation gain and discharge saving can be achieved with optimal use of limited water resource.

Keywords

Optimization – Unit Commitment – Economic Discharge Distribution

Introduction

Energy resources are the backbone of development for any country. Especially in developing countries as Nepal with the average GDP (PPP) per capita income around US$ 409 [1], it is of primary importance. Total energy consumption in the country has increased by about 2.4% per annum between the years 2000/01 and 2008/09 [2]. But, with the increasing growth rate of customers availing electricity services of NEA, the power and energy demand is also increasing accordingly. In 2015/16, the numbers of customers grew by 4.82% as compared to previous year [3]. Accordingly the peak power demand and energy demand also grew by 7.30% and 8.25%, respectively in that year [3].

Even though the peak power demand and energy demand has continuously increased, increase in electricity generation is not in par with demand. Total installed capacity of INPS grid (NEA-grid and IPP combined) 851.25MW only as compared to peak power demand of 1385.3MW [3]. This results in deficit of 534.05MW even in wet seasons. This difference is further exacerbated in dry months of year.

Construction of new hydropower plant is essential to meet the electricity demand. But, optimum utilization of existing power plants can also assist in meeting electricity requirement. Optimization problem of energy generation from a hydropower plant is that of unit commitment and economic load dispatch to different available units based upon difference in performance characteristics of different units. This preferential treatment is able to produce higher energy generation in comparison to equal distribution of discharge to all units because of the fact that performance of all units are not same due to several factors such as difference in length of waterways, alignment, manufacturing tolerances, wear of turbine parts, etc. for different units.

Hydropower plant may be subjected to another type of optimization problem. The plant may be required to generate power as per requirement from LDC. In this case, the optimization problem is not for maximizing generation but of meeting the power requirement with minimum total discharge of water. Since water is a limited resource in dry season, minimizing total discharge will result in availability of water for later use.

Study of optimal utilization of discharge through unit commitment conducted at Devighat Hydropower Plant has shown that additional gain in energy generation up to 6% is achievable for a ROR plant [4]. Study of reservoir operation of Hoa Binh River in Vietnam has shown that additional 3% gain in energy production can be achieved through optimization of reservoir operation [5]. A study conducted in Lower Colorado River system consisting of three power plants using dynamic programming determined that 1.8% increase in basin wide efficiency value can be obtained by optimal unit commitment [6]. A decision support system that addresses optimal unit dispatch and load allocation in a multi-unit Pensacola power plant of total installed capacity 90MW was able to obtain 1.9% improvement in annual energy generation [7]. Short term hydropower generation scheduling done on Xiluodu (12,600MW) and Xiangjiaba (6,000MW) cascaded hydropower stations located in Jisha River of China using binary coded bee colony optimization algorithm has shown that water saving of 1.36% of actual total water consumption can be achieved under same load conditions and river inflow [8]. Real-time operation optimization done on Itá Hydropower Plant (1450MW), located in southern Brazil, has shown a 0.28% lower outflow is required for same power requirement set by independent system operator [9].

This research is focused on optimizing operation of already existing Middle Marsyangdi Hydropower Station (2 Francis*35MW), located in Lamjung, Nepal.

1. Factors Influencing Unit Performance

Unit power is a function of

$$P = f(\eta, H, Q) \tag{1}$$

where,
η is unit efficiency, which depends upon net head and unit discharge,
H is unit net head, which depends upon total discharge,
Q is unit discharge.

But, unit net head is a function of

$$H = f(GH,\ \Delta h) \tag{2}$$

where,
GH is gross head,
Δh is head loss in waterways between reservoir and tailrace, which depends upon discharge.

Gross head of the plant is defined as,

$$Gross\ head\ \ (GH)\,, m = InL - TrL \tag{3}$$

where,
InL is intake level at reservoir, masl,
TrL is tailrace level= 518masl for MMHPS

Head loss from intake upto penstock bifurcation depends only upon total discharge flowing through the power tunnel system. Thus,

$$\Delta h_{bb} = InL - \left[\frac{P_{bb} * 10^5}{\rho * g} + \frac{1}{2g} * \left(\frac{Q}{A_{bb}}\right)^2 + z_{bb}\right] \tag{4}$$

where,
Δh_{bb} is headloss between intake and penstock bifurcation,m,
P_{bb} is pressure at penstock bifurcation, bar,
ρ is density of water= $1000 kg/m^3$,
g is acceleration due to gravity= $9.81 m/s^2$,
Q is total discharge through power tunnel system, m^3/s,
A_{bb} is area of penstock at bifurcation, m^2,
z_{bb} is elevation of penstock bifurcation, masl.

After bifurcation, head loss in each unit penstock is dependent upon water discharge in each unit penstock.

$$\Delta h_1 = InL - \left[\frac{P_1 * 10^5}{\rho * g} + \frac{1}{2g} * \left(\frac{Q_1}{A_1}\right)^2 + z_1\right] - \Delta h_{bb} \tag{5}$$

where,
Δh_1 is head loss in unit 1 penstock, m,
P_1 is pressure at end of unit 1 penstock, bar,
Q_1 is discharge through unit 1 penstock, m^3/s,
A_1 is area of unit 1 penstock, m^2,
z_1 is elevation of pressure tap of unit 1 penstock, masl.

Similarly,

$$\Delta h_2 = InL - \left[\frac{P_2 * 10^5}{\rho * g} + \frac{1}{2g} * \left(\frac{Q_2}{A_2}\right)^2 + z_2\right] - \Delta h_{bb} \tag{6}$$

where,
Δh_2 is head loss in unit 2 penstock, m,
P_2 is pressure at end of unit 2 penstock, bar,
Q_2 is discharge through unit 2 penstock, m^3/s,

A_2 is area of unit 2 penstock, m^2,
z_2 is elevation of pressure tap of unit 2 penstock, masl.

When unit 2 is shut down and only unit 1 is running, then $Q_2 = 0$, $Q = Q_1$ and $\Delta h_2 = 0$.

$$\left[\frac{P_{bb}*10^5}{\rho*g}+\frac{1}{2g}*\left(\frac{Q}{A_{bb}}\right)^2+z_{bb}\right]=\left[\frac{P_2*10^5}{\rho*g}+z_2\right] \tag{7}$$

Equations (4) and (5) become

$$\Delta h_{bb}, m = InL-\left[\frac{P_2*10^5}{\rho*g}+z_2\right] \tag{8}$$

$$\Delta h_1, m=\left[\frac{P_2*10^5}{\rho*g}\right]-\left[\frac{P_1*10^5}{\rho*g}+\frac{1}{2g}*\left(\frac{Q_1}{A_1}\right)^2\right] \tag{9}$$

Similarly, when unit 1 is shut down and only unit 2 is running, then $Q_1 = 0$, $Q = Q_2$ and $\Delta h_2 = 0$.

$$\left[\frac{P_{bb}*10^5}{\rho*g}+\frac{1}{2g}*\left(\frac{Q}{A_{bb}}\right)^2+z_{bb}\right]=\left[\frac{P_1*10^5}{\rho*g}+z_1\right] \tag{10}$$

Then, equations (4) and (6) become

$$\Delta h_{bb}, m = InL-\left[\frac{P_1*10^5}{\rho*g}+z_1\right] \tag{11}$$

$$\Delta h_2,\ m=\left[\frac{P_1*10^5}{\rho*g}\right]-\left[\frac{P_2*10^5}{\rho*g}+\frac{1}{2g}*\left(\frac{Q_2}{A_2}\right)^2\right] \tag{12}$$

Head loss also occurs during flow of water in draft tube. Head loss in draft tube of each unit is dependent upon discharge of water in each unit.

$$\Delta h_{d1}=\left[\frac{P_{d1}*10^5}{(\rho*g)}+\frac{1}{2g}\left(\frac{Q_1}{A_{d1}}\right)^2+z_{d1}\right]-TrL \tag{13}$$

where,
Δh_{d1} is unit 1 draft tube head loss, m,
P_{d1} is unit 1 draft tube pressure, bar,
A_{d1} is area of unit 1 draft tube, m^2,
z_{d1} is elevation of draft tube pressure, masl.

Likewise,

$$\Delta h_{d2}=\left[\frac{P_{d2}*10^5}{(\rho*g)}+\frac{1}{2g}\left(\frac{Q_2}{A_{d2}}\right)^2+z_{d2}\right]-TrL \tag{14}$$

where,
Δh_{d2} is unit 2 draft tube head loss, m,
P_{d2} is unit 2 draft tube pressure, bar,
A_{d2} is area of unit 2 draft tube, m^2,
z_{d2} is elevation of unit 2 draft tube pressure, masl.

So,

$$\Delta h_{total1} = \Delta h_{bb} + \Delta h_1 + \Delta h_{d1} \tag{15}$$

where,
Δh_{total1} is unit 1 total head loss, m.

Also,

$$\Delta h_{total2} = \Delta h_{bb} + \Delta h_2 + \Delta h_{d2} \tag{16}$$

where,
Δh_{total2} is unit 2 total head loss, m.

Thus,

$$H_1 = GH - \Delta h_{total1} \tag{17}$$

$$H_2 = GH - \Delta h_{total2} \tag{18}$$

where,
H_1 and H_2 are unit 1 and unit 2 net head, repspectively.

Finally,

$$\eta_1=\frac{P_1\times10^6}{\rho\times g\times H_1\times Q_1}*100\% \tag{19}$$

$$\eta_2=\frac{P_2\times10^6}{\rho\times g\times H_2\times Q_2}*100\% \tag{20}$$

where,
η_1 and η_2 are unit 1 and unit 2 overall efficiencies, respectively.

Since electrical output power was used instead of mechanical power, unit efficiencies represent efficiencies of the unit; not just mechanical efficiencies.

2. Optimization Model

2.1 Primal Optimization Problem

The main goal of the optimization model is to maximize daily energy generation of a hydropower plant. This can be done by operating the available units under optimal condition by economic dispatch of the available water flow at every instant of the day.

2.1.1 Objective Function

The objective function is

$$Maximize\, TDE = \sum_{t=0}^{86400} Max. \frac{(U_1 * P_1 + U_2 * P_2)}{3600} \quad (21)$$

where,
TDE is total daily energy generation, MWh,
U_1 is status of unit 1 at instant t,
U_2 is status of unit 2 at instant t, and
P_1 and P_2 are power generated by unit 1 and unit 2, respectively, at instant t, MW.

2.1.2 Constraints

The optimization model is subjected to following constraints

$$P_1 \leq 39.900MW, P_2 \leq 39.900MW \quad (22)$$

This limit is set by maximum capacity of unit generators.

$$U_1 = 0\ or\ 1,\ \ U_2 = 0\ or\ 1 \quad (23)$$

Binary limit of unit status represent the non-operational or operational state of each unit.

$$Q_1 \leq 50m^3/s,\ \ Q_2 \leq 50m^3/s \quad (24)$$

The limit on unit discharge is set by maximum allowable discharge through wicket gates of each unit.

$$Q_{total} = Q_1 + Q_2 \leq Q_{available} \quad (25)$$

where,
$Q_{available}$ is the available discharge. The total discharge used by both units cannot physically exceed the available discharge.

$$Q_1 = 0\ or > 15m^3/s,\ \ Q_2 = 0\ or > 15m^3/s \quad (26)$$

Unit discharge between 0-15m^3/s is avoided because this region is rough zone for unit generation during which vortices are induced in draft tube which lead to increase in cavitation. During operation, unit is ramped as fast as possible in this range.

$$P_1 \geq 0,\ \ P_2 \geq 0 \quad (27)$$

The non-negativity restrictions represent the generators will never operate in motor mode.

2.2 Dual Optimization Problem

The dual optimization problem for above primal optimization problem is to determine the minimum discharge that will be required to meet a particular load demand of the system.

2.2.1 Objective Function

The objective function is

$$Minimize\ Q_{total} = \sum_{t=0}^{86400} minimum\ (Q_1 + Q_2) \quad (28)$$

2.2.2 Constraints

Dual optimization problem is subjected to following constraints:

$$P_1 \leq 39.900MW,\ \ P_2 \leq 39.900MW \quad (29)$$

$$P_{total} = P_1 + P_2 \geq P_{required} \quad (30)$$

where, $P_{required}$ is the power demand in the grid.

$$U_1 = 0\ or\ 1,\ \ U_2 = 0\ or\ 1 \quad (31)$$

$$Q_1 \leq 50m^3/s,\ \ Q_2 \leq 50m^3/s \quad (32)$$

The optimization problem presented by both models are discontinuous non-linear optimization problems whose solutions are sought by non-linear generalized-reduced-gradient (GRG) method.

3. Data Collection

Supervisory Control And Data Acquisition (SCADA) system at MMHPS has a Historical Data Storage and Retrieval (HDSR) function which enables processed data to be recored for immediate analysis and for future reference. Primary data of Headrace level (masl), Total Discharge (m^3/s), Unit penstock pressure (bar), Unit Power (MW) and Unit draft tube pressure (bar) are extracted from HDSR. Necessary data for four driest months of the year are extracted.

4. Performance Analysis

4.1 Head Loss Calculation

Head loss in tunnel, in penstock before bifurcation and in unit penstocks after bifurcation are calculated using extracted data.

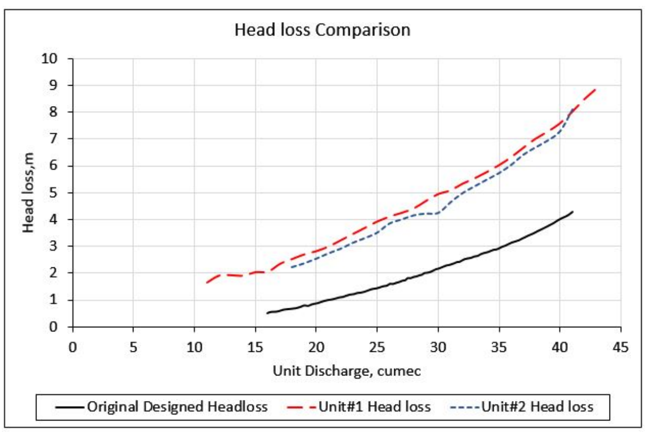

Figure 1: Comparison of Unit Head Losses with Designed Condition

From Figure 1, it is found that actual head losses are higher than the designed head loss for both units.

4.2 Turbine Hill Diagrams

Net head are calculated for individual units under all possible gross head and discharge conditions. Unit efficiencies for both units are calculated for all possible net head and discharge conditions to develop updated turbine hill diagrams as shown in Figure 2 and Figure 3.

The updated turbine hill diagrams confirms that there is a difference in performance between individual units. So, there would certainly be different outputs from different units under same head and discharge condition.

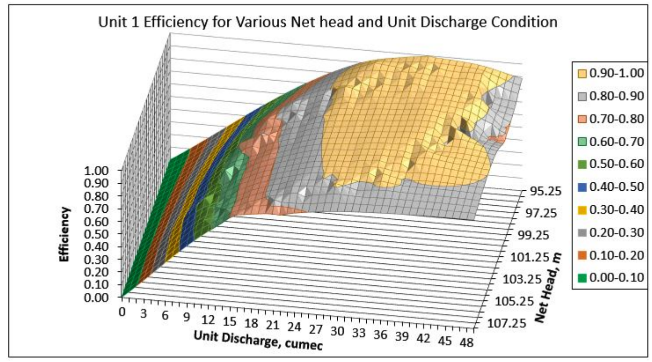

Figure 2: Unit 1 Efficiency for all Possible Conditions of Net Head and Unit Discharge

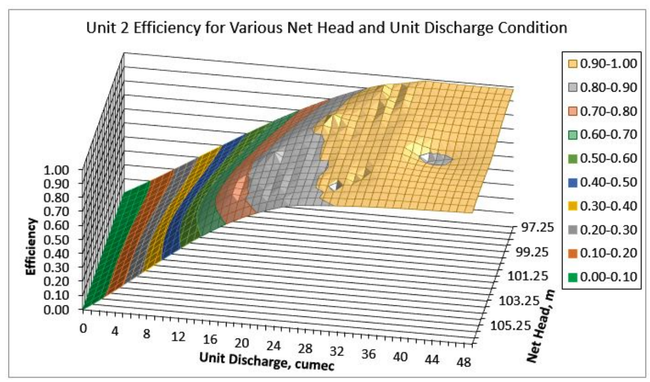

Figure 3: Unit 2 Efficiency for all Possible Conditions of Net Head and Unit Discharge

5. Optimization Result

Based on individual unit performance and head loss in hydraulic path of individual units, maximum power that can be generated for a particular gross head and total discharge is calculated using Solver tool in Microsoft Excel. Such calculations are repeated for all possible conditions of gross head and total discharge.

Figure 4 shows a matrix for optimal unit commitment. As shown by the figure, unit 1 should be run for all head and flow domain and unit 2 should be operated only when total discharge exceeds at least $42m^3/s$.

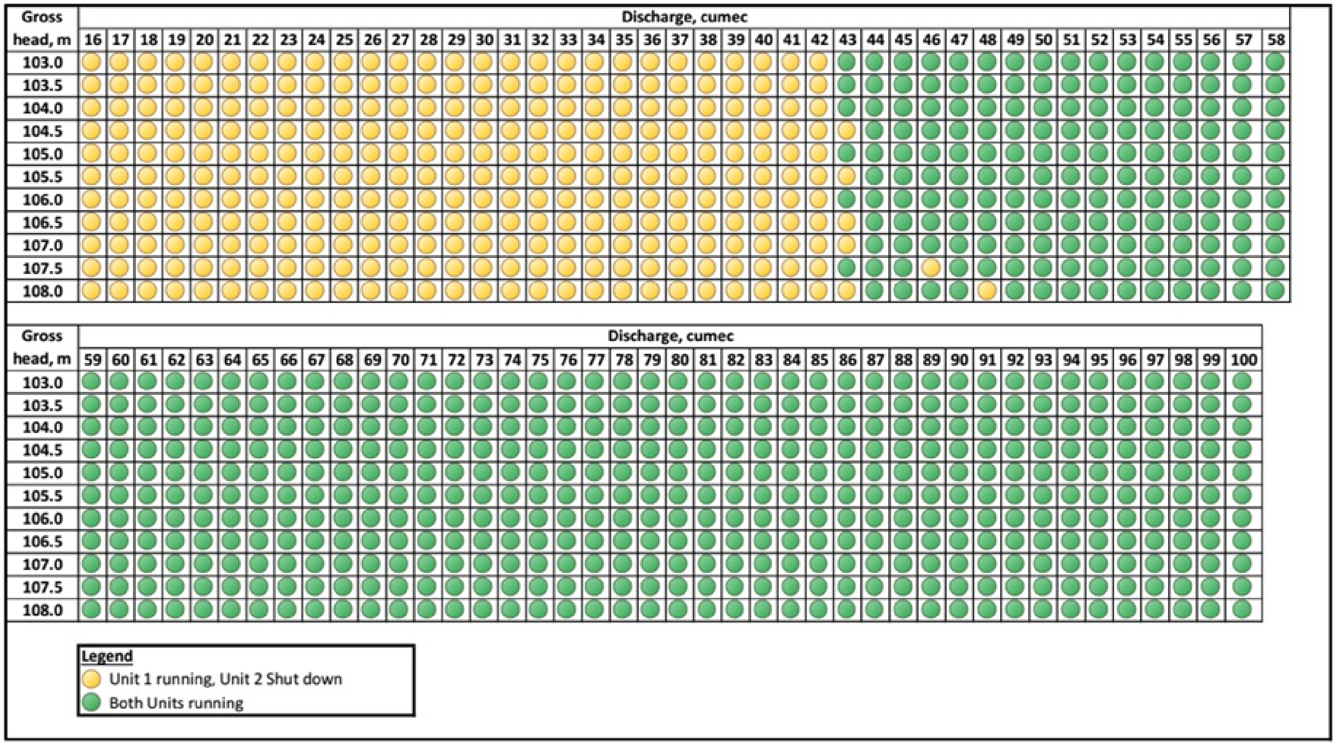

Figure 4: Optimum Unit Commitment

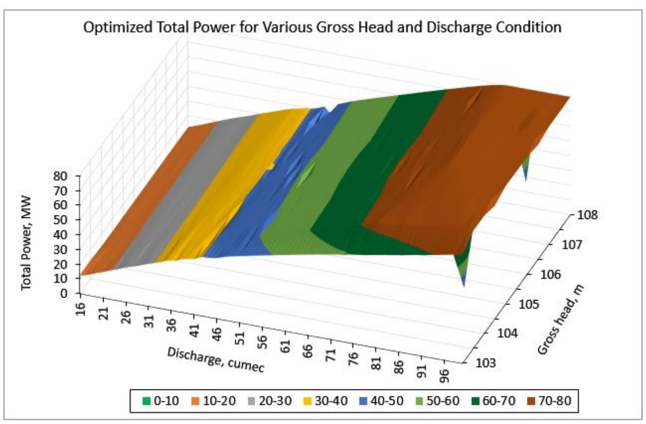

Figure 5: Optimum Total Power for all Possible Gross Head and Discharge Condition

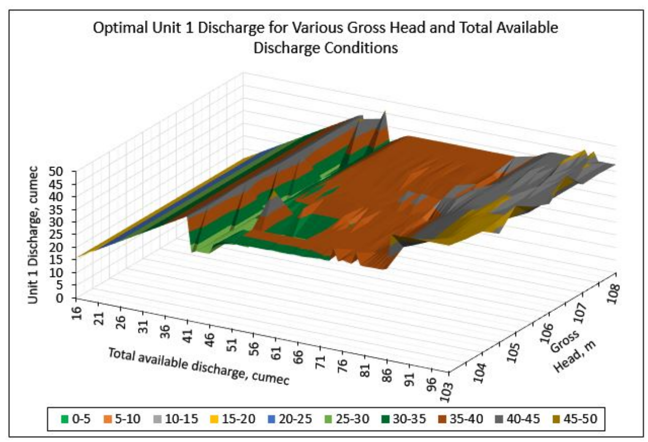

Figure 6: Optimum Unit 1 Discharge for all Possible Gross Head and Discharge Condition

The solution of primal optimization problem is represented in Figure 5. It shows optimal total power generated by the plant for all possible gross head and total discharge conditions. There are sharp drops in total power for discharge above $90m^3/s$ because the plant is operating beyond the designed operating range of the units.

Figure 6 and 7 represent discharge distribution in Unit 1 and Unit 2, respectively during optimum power generation.

Figure 8 graphically represents solution of dual optimization problem. It shows minimum total discharge that is required to meet power demand under various gross head conditions.

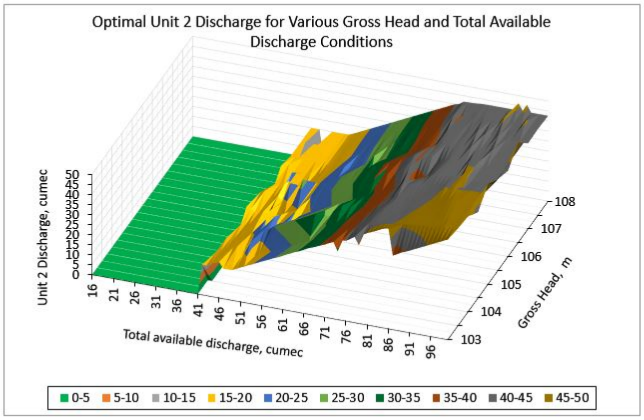

Figure 7: Optimum Unit 2 Discharge for all Possible Gross Head and Discharge Condition

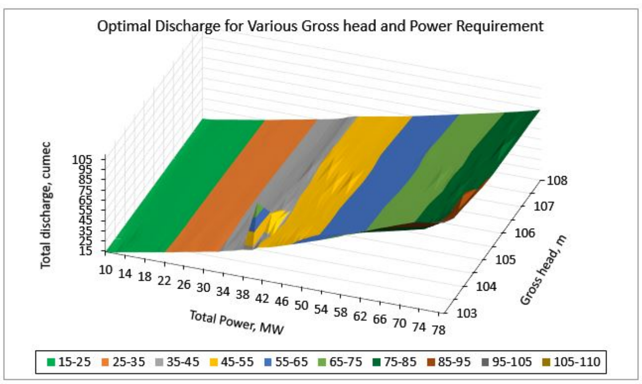

Figure 8: Optimum Total Discharge for all Possible Gross Head and Power Requirement Conditions

6. Historical Operation Optimization

Since the plant was not operated in optimal manner, there exists a possibility of generation gain and discharge saving.

Generation and total discharge of each second for eight random days from low discharge availability period are extracted from HDSR. Primal optimization is used to determine the generation gain from the same total discharge that was available to the plant operator. Similarly, dual optimization is used to determine the discharge saving that would have been possible for same power requirement of the system.

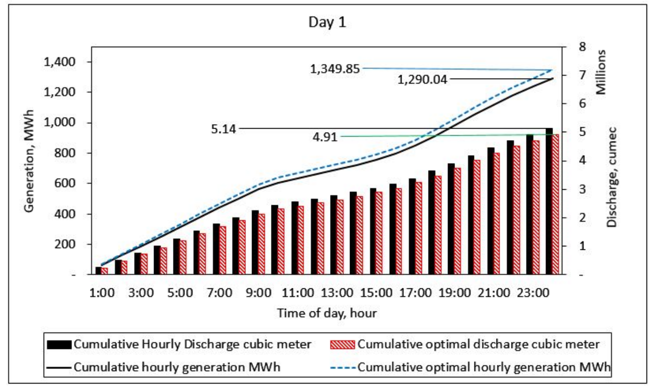

Figure 9: Comparison of Optimized Total Power and Discharge with Actual Operation of Day 1

Figure 9 compares the actual operation data with the optimal solution result for Day 1. Cumulative optimal energy generation is always higher than actual generation and cumulative optimal water consumption is always lower than actual water consumption for all instant of the day.

Table 1 represents the output of the optimization applied to the operational data for eight random days of low discharge availability period. It shows that additional energy upto 7.20% can be added with optimal use of available water and upto 4.96% discharge could be conserved.

7. Conclusion

This paper presents a methodology for operation optimization of an existing hydropower plant. It is shown that operational data can be used to determine head losses and performance of individual units within a hydropower plant. It is observed from updated turbine hill diagrams and solution of optimization model that difference between performances of individual units should be exploited to obtain additional generation with same amount of water used and to conserve the amount of water used to generate same amount of energy. The study provides a decision support system to plant operators for optimal unit commitment and economic discharge distribution. Finally, beyond benefits from optimal use of limited water resource, the study also provides a guide to improve technical and economic performance of a plant.

Table 1: Operation Optimization of MMHPS for Eight Random Days during Dry Season

Day	Actual Generation MWh	Actual Discharge cumec	Optimal Generation MWh	Generation Gain MWh, %	Minimal Discharge cumec	Discharge Saving cumec, %
1	1,290.04	5,142,241.36	1,349.85	59.82, 4.64%	4,909,829.21	232,412.15, 4.52%
2	1,324.24	5,249,098.16	1,385.88	61.63, 4.65%	5,014,254.66	234,843.50, 4.47%
3	1,173.56	4,708,093.94	1,236.01	62.46, 5.32%	4,474,397.79	233,696.14, 4.96%
4	1,110.71	4,410,754.97	1,190.64	79.93, 7.20%	4,218,560.43	192,194.53, 4.36%
5	969.95	3,856,898.28	1,010.22	40.27 , 4.15%	3,705,987.96	150,910.32, 3.91%
6	821.32	3,206,676.44	834.94	13.62, 1.66%	3,156,133.74	50,542.70 , 1.58%
7	775.72	3,039,147.56	790.69	14.97, 1.93%	2,990,595.95	48,551.61, 1.60%
8	759.61	3,036,136.78	782.74	23.13, 3.04%	2,948,504.50	87,632.29, 2.89%
Generation Gain/ Discharge Saving				1.66-7.20%		1.58-4.96%

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References

[1] IEA. Key world energy statistics, 2015. Technical report, International Energy Agency, 2015.

[2] WECS. Energy sector synopsis report. Technical report, Water and Energy Commission Secretariat, 2010.

[3] NEA. A year in review- fiscal year 2015/2016. Technical report, Nepal Electricity Authority, 2016.

[4] Suraj Dahal. Operation optimization and performance evaluation of devighat hydropower plant. 2013.

[5] Henrik Madsen, Bertrand Richaud, Claus B. Pedersen, and Carter Borden. A real-time inflow forecasting and reservoir optimization system for optimizing hydropower production. In *Waterpower XVI*. PennWell Corporation, 2009.

[6] Jaeeung Yi, John W. Labadie, and Steven Stitt. Dynamic optimal unit commitment and loading in hydropower systems. *Journal of Water Resources Planning and Management*, pages 388–398, 2003.

[7] Jim Cook and Jim Walsh. Optimization of hydro-power plants for generation. In *IGHEM Conference 2008*, page 10, 2008.

[8] Peng Lu, Jianzhong Zhou, Chao Wang, Qi Qiao, and Li Mo. Short-term hydro generation scheduling of xiluodu and xiangjiaba cascade hydropower stations using improved binary-real coded bee colony optimization algorithm. *Energy Conversion and Management*, pages 19–31, 2015.

[9] M.M. Cordova, E.C. Finardi, F.A.C. Ribas, V.L. de Matos, and M.R. Scuzziato. Performance evaluation and energy porduction optimization in the real-time operation of hydropower plants. *Electric Power Systems Research*, pages 201–207, 2014.