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Sand Erosion on Turbine Components: A Case Study of Kaligandaki "A" Hydropower Station

Pawan Ghimire[1], Dr. Mohammad Tariq[2]

[1]M tech Student VIAET, Department of Mechanical Engineering

[2]Assistant Professor, VIAET, Department of Mechanical Engineering

Abstract: ***Even though electricity supplies only about 6% of total energy demand of Nepal, it being the cleanest form of energy, there is an increasing demand for it. Rapid urbanization, population growth and technological development help to further increase the demand of electricity. But, total installed capacity of hydropower plants in Nepal is very low and total generation from all these plants is inadequate to meet the demand. There exists capacity shortage of electricity. Due to low river discharge in dry seasons, this capacity shortage is further exacerbated resulting high load shedding hours. To rectify this capacity shortage, either new plants are to be constructed or operate existing plants in a more efficient way. Construction of new plants require large investment and gestation period, so for present context optimization of existing plant is the best option. Among different possible optimization methods, type 1 and type 2 optimization were carried out in KGAHPP as this being the largest plant in operation in Nepal (144MW). The results from type 1 and type 2 optimization justify the effort, time and money invested***

Keywords: KGAHPP, optimization, gain

1. Introduction

Electricity contributes about 6% in the total energy supply of Nepal. Almost 90% of demand of electricity is met by electricity produced by Hydropower Plants. In the present context of Nepal the demand of electricity has exceeded the amount of electricity that can be supplied by Nepal Electricity Authority (NEA). As a result NEA is importing electricity from India and producing electricity from fossil fuel for short term preventive measures. Even after implementation of preventive measures the peak demand has not been met. The problem of the optimum management of hydropower plants includes the optimum management of a unit with the minimum water consumption per unit of generated electricity. In modelling of the hydropower plant operation it is necessary to adhere to the limitations imposed by the characteristics of the plant itself, as well as to the other conditions present on a certain watercourse.

Planning of hydropower plant operation, as well as the simulation of its operation, can be short-term or long-term oriented. The main source of uncertainty in planning of development of an electricity generation is the stochastic nature of availability of the units as well as the water inflow into hydropower plants. Limited availability of water in dry season and optimized use of this would help to produce more hydro electricity from same amount of discharge which in term will help to reduce electricity import from India, & operation time of Diesel Power Plants. Also optimization of limited discharge during dry season helps to slightly reduce load shedding hours, the optimization of hydropower systems can be conveniently performed by the means of simulation of their operation. By simulation it is possible to analyze numerically the situations that would be unsafe or ineffective to observe on an actual plant. The simulations are based upon the mathematical models, whose technical task is to describe as accurate as possible the properties of physical objects.

The main objective of the article is to study recent performance, current operation practice of Kaligandaki "A" Hydroelectric Power Plant and develop a relation for determining the optimum combinations of the units of the plants during low level operation and then develop an optimization program for optimum operation.

2. Materials and Methods

This study is based on both qualitative and quantitative information. The data is based on both primary and secondary data field. Primary data were taken from Kaligandaki "A" hydro power plant. Secondary data were collected from other various sources.

a) Primary Data Collection

The primary data were measured using various equipment located in the power plant, such as flow meter, level sensor, energy meters etc. were used to measure different outputs; also data were collected from various displays located at different panels of control room. Data stored on memory of control room computers were also collected. The hourly analogue data maintained by Shift In-charge on daily log sheets were taken and upgraded to digital data.

b) Secondary Data collection

Secondary data was collected from different offices of Nepal Electricity Authority (NEA) such as Load Dispatch Centre (LDC) and Office of Generation, Operation and Maintenance. Various related publications, reports, literatures, studies, etc. have been collected from different related offices. Beside these, related information was also collected from related web sites.

c) Performance Analysis of Hydro Power Plant

All the quantitative data obtained have been encoded in Microsoft Excel program and driving variable have been analysed. For the performance optimization of hydro power plant, it is necessary to analyse existing performance of hydro power plant such as power output of hydro power plant with variable discharge, head, and efficiency.

Different performance indices, such as overall plant efficiency, individual unit efficiencies, availability of units, availability of plant, plant capacity, capacity factor, etc., have been calculated before and after type I optimization.

d) Plant availability

It refers to the time during which the plant is available for running (capacity state probability, Pi).

When all plant units are up = ∏ Aj for all j.

When all plant units are down = ∏ (1 - Aj) for all j.

For a 3-unit plant, when 2 units are up and 1 unit down =

$$\sum_{i\neq j} A_i A_j (1 - A_k);\ i,j,k = 1,2,3$$

For a 3-unit plant, when 2 units are down and 1 unit up =

$$\sum_{i\neq j\neq k} A_i (1 - A_j)(1 - A_k);\ i,j,k = 1,2,3$$

Above relations can be summarized for KGAHPP having three units as follows:

Table 1: Plant Availability of 3 Unit Plant.

Capacity State				Plant Availability
	Unit 1	Unit 2	Unit 3	$A_1A_2A_3$
All Up	Up	Up	Up	
2 Up 1 down	Up	Up	Down	$A_1A_2R_3$+ $R_1A_2A_3$+ $A_1R_2A_3$
	Down	Up	Up	
	Up	Down	Up	
1 Up 2 down	Up	Down	Down	$A_1R_2R_3$+ $R_1A_2R_3$+ $R_1R_2A_3$
	Down	Up	Down	
	Down	Down	Up	
All down	Down	Down	Down	$R_1R_2R_3$

3. Optimization

Optimization is the process of finding the conditions that give maximum or minimum value of a function. Optimization within a concept most often has to do with operational methods of a system where the most optimum output is sought. It applies to existing or already designed systems.

For hydro power plants, optimization means either a) producing more power from same discharge, or b) using less discharge to produce the desired amount of power or c) combination of both a and b. In the 1980s, the Bonneville Power Administration, U.S. Army Corps of Engineers and other federal agencies collaborated to define five "types" of optimization pertaining to hydropower as listed below:

- Type 1: Optimization of an individual unit in terms of power output per amount of flow at constant head;
- Type 2: Coordination of generating units to achieve a powerhouse output set point using the least amount of flow. This level of optimization is achieved with the best possible unit selection and load sharing;
- Type 3: Coordination of all the dams and hydroelectric powerhouses in a river basin or watershed;
- Type 4: Coordination of multiple river basins and watersheds in a region; and
- Type 5: Coordination of all of a region's various generating resources.

When a power set point is chosen, the powerhouse operator can choose to have some turbines on and some off, a process called unit selection. The next parameter to determine is load sharing. The best load sharing is achieved when the wicket gate openings for all turbines are set individually, such that the power output is met using the minimum overall flow rate or more power is produced from same flow rate.

Both decisions are more difficult to determine than they might seem. Even a skilled hydroelectric plant operator may lose up to 5% of the water available for use ideal unit selection and optimized load sharing. During conditions where water must be spilled, that 5% may not make a lot of difference. However, when the flow of the river is insufficient to meet the net energy demand, this 5% can represent a significant corresponding loss of generation resulting in loss of revenue.

a) Solver

Solver is part of a suite of commands sometimes called what-if analysis tools. With Solver, you can find an optimal (maximum or minimum) value for a formula in one cell — called the objective cell — subject to constraints, or limits, on the values of other formula cells on a worksheet. Solver works with a group of cells, called decision variables or simply variable cells that participate in computing the formulas in the objective and constraint cells. Solver adjusts the values in the decision variable cells to satisfy the limits on constraint cells and produce the result you want for the objective cell.

b) Optimization Using Flow Measurement

For a given constant power output, the efficiency is inversely proportional to the input power, i.e., for a given dispatched power, the maximum efficiency will be reached when the summation of the hydraulic power at the turbines input is minimized. The hydraulic power (in kW) is given by:

$P_h = g.HN.\ Q$

$Q = P_h / (g.HN)$

Where, g is the gravitational constant (m/s²), Q is the input flow (m³/s), and HN is the net head (m) obtained

As long as the hydraulic power is proportional to the input flow, and that the maximum efficiency is obtained when the flow is minimum, the optimization system can be rewritten as follows:

$$\min Q_T = \sum_{j}^{n} Q_j$$

s.t $\sum_j^n \mathrm{Pj} = \mathrm{Pd}$

$P\ jmax \geq P\ j \geq P\ jmin$

where, Qj is the input flow in the j-th unit, and QT is the total flow given by the summation of the n individual flows.

The controller must search the power allocation between the units aiming at minimizing the total flow. Therefore, the user has access neither to the unit efficiency nor to the overall efficiency, but is sure that it is operating over the most economical point by minimizing the amount of the necessary fuel, the water, for a given dispatched power.

The model developed during this research is based on offline optimization process using flow measurement. Offline optimization model was developed using Solver in MS Excel. The objective function to be maximized was developed with help of efficiency characteristic against percent discharge of each unit. Efficiency characteristic was developed using data from field test. From regression analysis of field test data, smoothened efficiency characteristics of Unit 1, Unit 2 and Unit 3 were obtained as follows:

$$\eta_1 = 0.9474\ Q_1^3 - 2.8708\ Q_1^2 + 2.9368\ Q_1 - 0.0906 \quad (1)$$

$$\eta_2 = 0.9357\ Q_2^3 - 2.8713\ Q_2^2 + 2.9598\ Q_2 - 0.0937 \quad (2)$$

$$\eta_3 = 0.8352\ Q_3^3 - 2.6771\ Q_3^2 + 2.8494\ Q_3 - 0.0820 \quad (3)$$

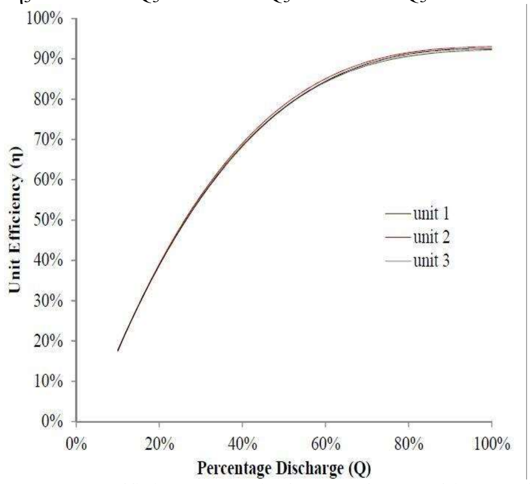

Figure 1: Efficiency vs Discharge of a 3 turbine Hydro Power Plant

With aid of above mentioned three equations, equation for unit power and total power output of the plant were obtained to be

$$P_1 = 9.81 \text{ X } 115 \text{ X } Q_1 \text{ X } \eta_1 \quad (4)$$

$$P_2 = 9.81 \text{ X } 115 \text{ X } Q_2 \text{ X } \eta_2 \quad (5)$$

$$P_3 = 9.81 \text{ X } 115 \text{ X } Q_3 \text{ X } \eta_3 \quad (6)$$

$$P_{total} = P_1 + P_2 + P_3 \quad (7)$$

Equation (7) represents total power produced for the plant at any instant which is a function of discharge only. It has been assumed that head is constant throughout the optimization process. This is the objective function for the optimization which is subjected to following constraints:

Non-negativity constraints: $Q_1, Q_2, Q_3, \eta_1, \eta_2, \eta_3, P_1, P_2, P_3, P_{total} \geq 0$

Bounding constraints: $Q_1, Q_2, Q_3 \leq 46m3/s$
$\eta_1, \eta_2, \eta_3 \leq 100$,

This mathematical model represents actual physical behavior of power production in KGAHPP.

4. Results and Discussions

Plant optimization was carried out in KGAHPP from Shrawan 2074 to Ashad of 2075. So, for comparison, twelve-month data are available for fiscal year 2074/75. Different power plant performance indices before and after Optimization were calculated with help of data listed in Annex.

Plant capacity is a measure of energy the plant is capable of generating. It is dependent on power generation of the plant and the corresponding running hours. For Kaligandaki "A" Hydro Power Plant, the total plant capacity as follows:

PC = Installed Power (MW) × Running Hours (H)
Before Optimization,
PC = 144MW × 24hrs × 365 (days)
PC = 1261440MWh

An offline model for optimization of unit commitment and discharge distribution for optimal power generation has been developed. This model have been verified using generation and discharge measurement of fiscal year 2074/75 and calculations have been done to find out the results that would have been gained if optimization has been implemented.

After Optimization,
PC = 147.02MW × 24hrs × 365 (days)
PC = 1287895 MWh

Plant capacity has been increased from 1261440 MWh to 1287895 MWh due to optimization.

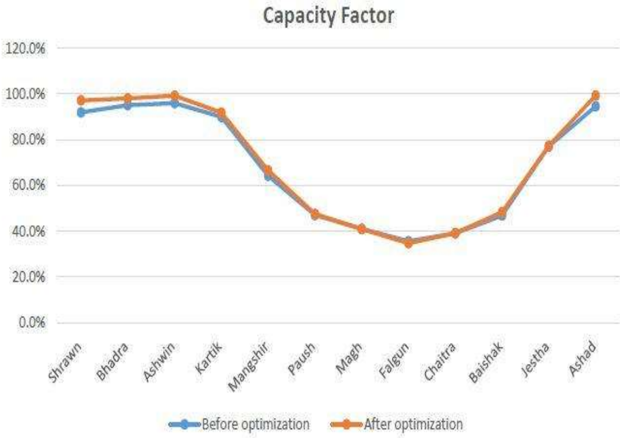

Figure 2: Capacity factor of KGAHPP before and after optimization

This shows that after optimization, the average capacity factor for KGAHPP is 70.5%, with a minimum of 34.7% for the month of Falgun and a maximum of 99.3% in the month of Ashwin. Before optimization, the average capacity factor for KGAHPP is 68.6%, with a minimum of 35.6% for the month of Falgun and a maximum of 96% in the month of Ashwin. Capacity factor of the plant after optimization is enhanced for every months considered except for Falgun during analysis which is because of the lowest discharge in river. This indicates that after the optimization, failure rate and downtime of the plant/units have significantly reduced with increase in generation.

Figure 3: Average gain and actual gain of KGAHPP after optimization

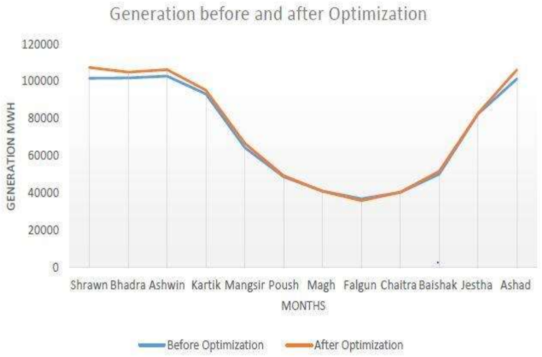

Figure 4: Generation of KGAHPP before and after optimization

From Figure 4 and Figure 5, it is clearly seen that gain is always positive and generation after optimization is higher than that before optimization for all months under consideration (except for Falgun). This validates the effort taken for optimization.

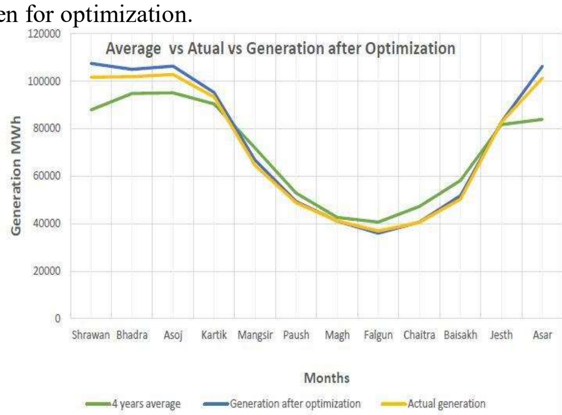

Figure 5: Generation comparison of KGAHPP before and after optimization to average generation

Figure 5 shows the plot of average generation of past 4 years and optimized generation, which shows that in wet season there is improvement in generation and even after optimization there is lag in generation in dry season which clearly shows that it needs serious study of hydrology and its data as well as efficient operation and maintenance of KGAHPP.

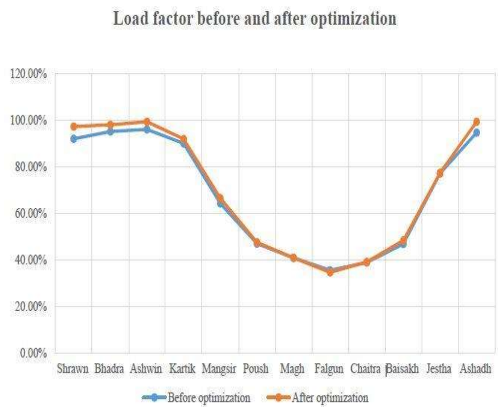

Figure 6: Load factor before and after optimization of KGAHPP

From figure 6 it is seen that LF has been enhanced due to optimization, except for month of Falgun where LF is slightly reduced after optimization.

Maximum generation before optimization is in the month Ashwin with load factor of 96.0%. After optimization, maximum generation is in month Asar with load factor of 97.2% which is significantly higher than that before optimization. From the table and graph it is seen that the load factor of plant is improved significantly before and after optimization.

Figure 7: Gain and % gain after optimization of KGAHPP

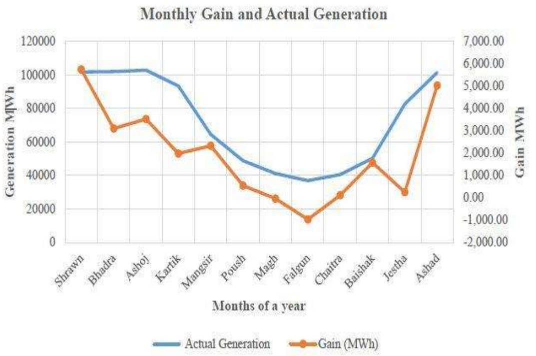

Figure 8: Monthly gain and actual generation of KGAHPP after optimization

Figure 8 shows that during dry months or when discharge is low, although gain is less it is more significant because of low overall generation whereas demand is high that leads to more energy import.

So optimization is effective and relevant during dry months. Being a semi storage type of plant it becomes more important to meet the peak hour load demand and to reduce generation when demand is low or even plant shut down for certain time when demand is low. Where as in high discharge months it is important to have high gain and generate more energy that eventually results into high plant utilization.

Although there seems some drop in gain, overall there is gain of 2% and due to optimization it is seen that there is saving of discharge as well. Being a semi storage type of plant that saving in discharge plays a crucial role to meet the peak hour demands.

5. Conclusion

Optimization helps to enhance performance of units in a power plant resulting in better generation with better performance indices- reliability, forced outage rate, MTBF, MTTR, availability, capacity factor, load factor, PUF and utilization factor. Large amount of investment is required for type 1 optimization with certain period of no power output. Hence, prior economic and financial analysis should be performed before committing for type 1 optimization. Nevertheless, type 1 optimization is capable of enhancing generation by reducing failures and improving performance characteristic of units. Type 2 optimization is lucrative in a sense that it doesn't require plant shut down and requires only a small amount of investment and effort to create opportunity for enhanced generation from existing units. Type 2 optimization is best suited for dry season (low discharge periods) when there is an acute deficit in energy supply in the system. For KGAHPP, type 2 optimization can result in 2.1% (26455MWh) enhancement in generation which is equivalent to addition of 3.02 MW plant in the system without any additional investment and environmental cost. Plant control system upgradation is being carried out on the plant which will give the more accurate and real time data and using those data further detailed study has to be performed for better results.

Limitations

- Efficiency measurements for different units were carried out for Average head (115m) only due to regulation from Load Dispatch Centre. (LDC).
- Efficiency was back-calculated from other measurements only due to lack of direct efficiency measuring equipment and method.
- During Rainy season because of high sedimentation outage was high for flushing works in settling basin.
- LDC doesn’t allow plant to run in fixed load as it is the largest plant in the country that take care of the load fluctuation in the system.

6. Recommendations

Some recommendations for future enhancement of the work are given below:

- Efficiency measurements for analysis should be carried out for various heads (high, medium and low).
- Direct efficiency measurement device and methods should be employed for more accurate results.
- Because of high sediment deposited on reservoir area it may not give the actual discharge so proper sediment study and re-establishment of reservoir data is needed.

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