Operation Optimization and Performance Evaluation of Devighat Hydropower Plant

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***Abstract*: Hydropower plant optimization is to maximize electrical energy production depending on the natural water inflows of a river. Two different types of optimization were carried out in Devighat Hydro Power Plant (DHPP). Among different possible optimization methods, Type I and Type II optimization were carried out in DHPP. Type I optimization deals with enhancing the efficiencies of individual units of the plant with help of overhauling or rehabilitation process resulting in enhancement of generation. Type II optimization deals with modeling an optimal hydro unit commitment and loading for maximizing generation. The results from Type I and Type II optimization justify the efficient generation in terms of effort, time and money invested.**

Keywords: Optimization, Generation, Efficiency, Units

1. INTRODUCTION

Electrical energy being the cleanest form of energy, there is an increasing demand for it. Rapid urbanization, population growth and technological development enhance to further increase the demand. Almost 90% of demand of electricity in Nepal is met by electricity produced by Hydropower Plants. But, total installed capacity of Hydropower Plants in Nepal of 750 MW is very low and inadequate to meet the demand of electricity which is 950MW. So there is shortage of electricity. For the fiscal year 2011/12, the total Annual Energy Demand was estimated to be 5194.78 GWh and annual Peak Power Demand was estimated to be 1026.65 MW with NEA able to supply only 4178.63 GWh. The annual increase in total Annual Energy Demand was 7.48% and the annual increase in Peak Power Demand was 8.5% as compared to previous year (NEA, 2012). From this scenario of power supply and demand situation of Nepal it is clear that there is generation shortage**.** Except Kulekhani Ist and IInd Hydro Power Plant, all Hydropower Plants of Nepal are Run of River (ROR) type, so due to low river discharge in dry seasons, this capacity shortage is further exacerbated resulting in high load shedding hours.

The best option to meet growing demand is to improve capacity of NEA either by installation of new Hydropower Plant or by improving efficiency of existing plants. Hydroelectric generation is a function of discharge, net head and efficiency factor of generating units. Efficiency factor is in turn a function of the flow and available net head.

The problem of the optimum management of hydropower plants includes the determination, for each unit in the hydropower plant, whether it is in operation under the given operating conditions, i.e. in which operating regime it operates.

The optimization of hydropower systems can be conveniently performed by the means of overhauling or rehabilitation process and simulation of their operation. The simulations are based upon the simulation mathematical models, whose technical task is to describe as accurate as possible the properties of physical objects.

2. DATA FOR PERFORMANCE ANALYSES

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 Devighat Hydro Power Plant. Secondary data were collected from other various sources.

2.1. Primary Data Collection

The primary data needed for performance analysis include unit characteristics data, facility operational data, and facility hydrological data.

The primary data was measured by using various equipments located in the Power Plant. Devices such as flow meter, level sensor, energy meters etc. were used to measure different outputs. 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.

Plant was shut down from Magh 2067 to Ashad of 2068. So analysis of generation during this duration could not be performed. DHPP being cascade plant of THPP, discharge was regulated by THPP. So in month of Ashad 2069, even during wet season generation from DHPP was similar to dry season generation due to unit shutdown in THPP. This resulted in slight deviation from general pattern during analysis.

2.2. Collection of Secondary Data

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.

2.3. Performance Analysis of Hydro Power Plant

All the quantitative data obtained have been encoded in Microsoft Excel program and driving variable were 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, MTTR, MTBF, etc., have been calculated before and after Type I optimization.

2.4. Devighat Hydropower Plant

Devighat Hydropower Plant with an installed capacity of 14.1 MW (3 x4.7 MW) is located at 70 km Northwest of Kathmandu on the right bank of Trishuli river. It is a tailrace development of Trishuli Hydropower Plant. It was commissioned in the year 1984. The average (Designed) annual generation of this power plant is 114 GWh.

The hydropower plant consists of three units of 5 MW each. Its power generating capacity has been rehabilitation from initial 14.1 MW (3 x4.7 MW) to 15 MW (3 x 5 MW). The three units have been upgraded with state-of-the-art system.

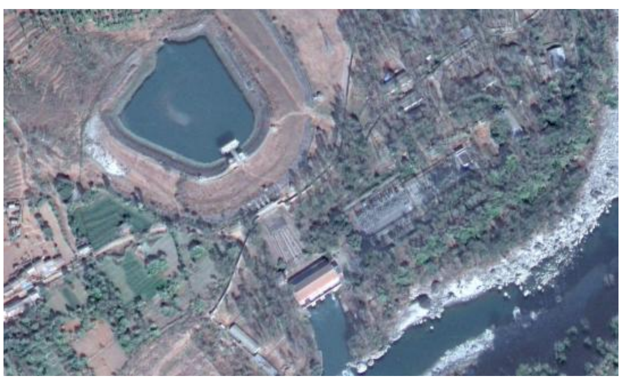

Figure 1: Satellite view of Devighat Hydropower Plant

3. OPTIMIZATION AND MODEL DEVELOPMENT

3.1. Type I optimization

Type I optimization was carried out in DHPP from Magh of 2067 to Ashadh of 2068. So, for comparison, only six-month data were available for fiscal year 2067/68 (i.e. before rehabilitation). During the rehabilitation, all electro-mechanical components were replaced with state-of-art technology. Different power plant performance indices before and after rehabilitation were analysed (Type I Optimization).

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. The total plant capacity of Devighat Hydro Power Plant, as follows:

PC = Installed Power (MW) × Running Hours (H)

Before T1 Optimization,

PC = 14.1MW × 24hrs × 365 (days)

PC = 123,516 MWh

After T1 Optimization,

PC = 15MW × 24hrs × 365 (days)

PC = 131,400 MWh

Plant capacity of DHPP has been increased from 123,516MWh to 131,400MWh due to T1 optimization. This was possible due to efficiency enhancement of power plant after T1 optimization.

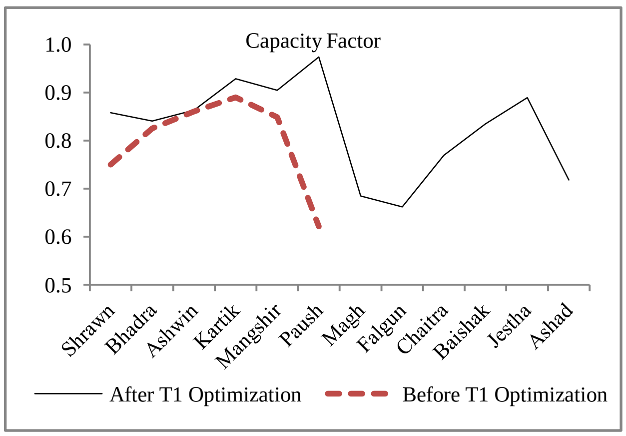

Figure 2: Comparison of Capacity Factor before and after T1 Optimization

This shows that after T1 optimization, the average capacity factor for DHPP is 82.73%, with a minimum of 66.19% for the month of Falgun and a maximum of 97.38% in the month of Poush. Before T1 optimization, the average capacity factor for DHPP was 79.94%, with a minimum of 62.15% for the month of Poush and a maximum of 88.97% in the month of Kartik. These capacity factors are within and above utility best practice of between 50% and 80%. Capacity factor of the plant after T1 optimization is enhanced for every months considered during analysis. This indicates that after the optimization, failure rate and downtime of the plant/units have significantly reduced with increase in generation.

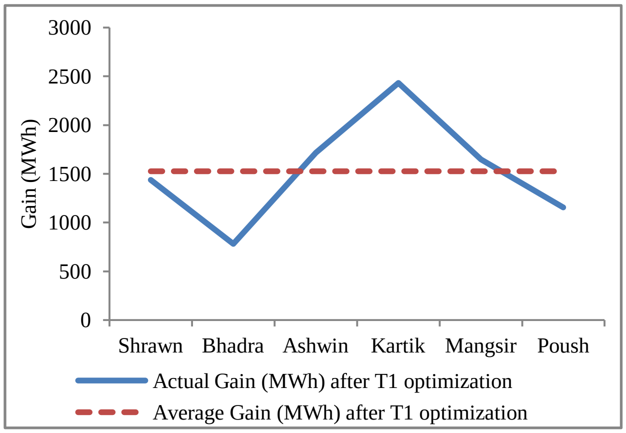

Figure 3: Actual and Average gain after T1 Optimization

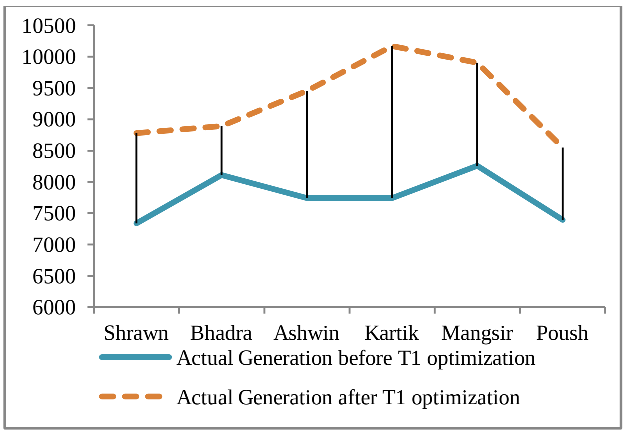

Figure 4: Actual generation before and after T1 Optimization

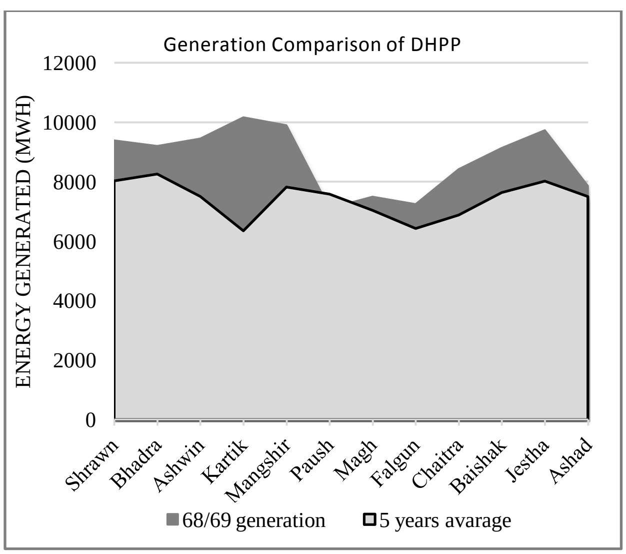

Figure 5: Comparison of 68/69 generation
5 years average of DHPP

From Figure 3 and Figure 4, it is clearly seen that gain is always positive and generation after T1 optimization is higher than that before T1 optimization for all months under consideration. This validates the effort taken for rehabilitation. Figure 5 and Figure 6 also justify generation enhancement due to T1 optimization.

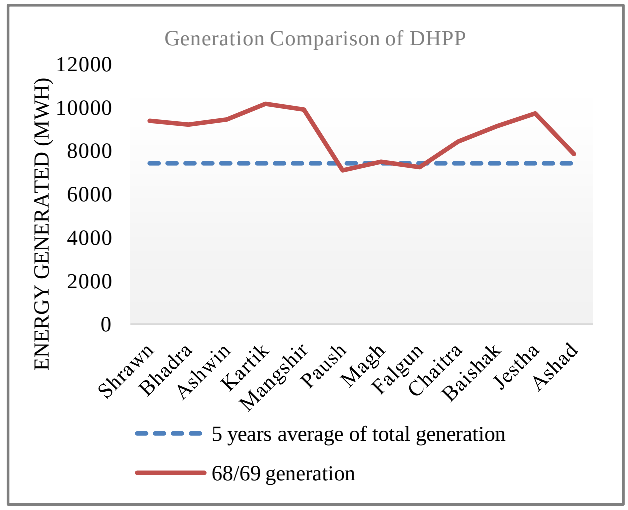

Figure 6: Comparison of 68/69 generation with 5 years average of Total Generation of DHPP.

Table 1: Monthly performance indices before and after T1 Optimization

	Plant Use Factor (PUF)		Load Factor (LF)	
	067/68	068/69	067/68	068/69
Shrawn	77.74%	84.05%	77.37%	93.07%
Bhadra	81.96%	86.56%	85.50%	91.22%
Ashwin	80.82%	90.55%	81.58%	93.68%
Kartik	80.82%	95.16%	81.58%	100.76%
Mangsir	96.54%	95.63%	87.03%	98.12%
Poush	83.62%	98.92%	77.92%	70.44%
Magh	-	81.69%	-	74.30%
Falgun	-	74.36%	-	71.82%
Chaitra	-	82.67%	-	83.48%
Baisakh	-	83.49%	-	90.56%
Jestha	-	86.30%	-	96.47%
Ashadh	-	73.61%	-	77.31%

Both PUF and LF have been enhanced due to Type I optimization, except for month of Mangsir where PUF is slightly reduced after rehabilitation. Maximum generation before optimization is in the month Mangsir with utilization factor of 80.22%. After optimization, maximum generation is in month Kartik with utilization factor of 92.88% which is significantly higher than that before optimization.

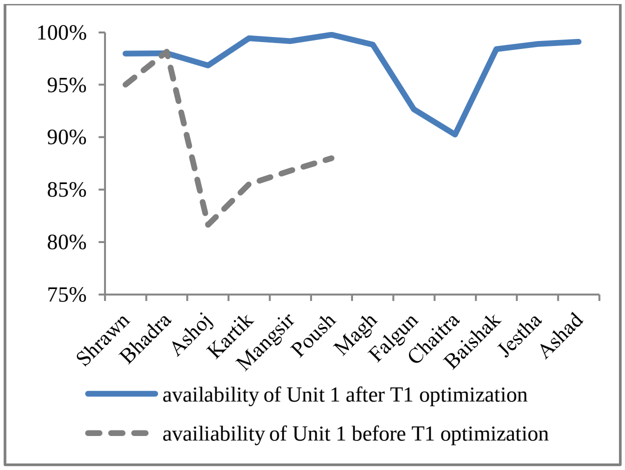

Figure 7: Availability of Unit 1 before and after Type1 Optimization

Figure 7 shows availability of the unit 1 before and after optimization. It is seen that the availability before the optimization was very low which have been significantly improved by the optimization.

3.2. Type II Optimization

Unit efficiencies were calculated for a constant high head (40m) at varying discharge for individual unit with the help of discharge measurement, head measurement and unit energy generation measurement. Mathematical model of efficiency versus discharge was developed for each unit. This mathematical model was used to optimize total power generation of the plant over total discharge regime using Solver function in MS Excel. The Solver function was used to optimize total power by distributing discharge and committing unit with maximum efficiency in the discharge range. The results of Solver function was also verified using a mathematical optimization program developed in C programming language.

3.3. Optimization System Design

The developed optimization system is applied to Devighat Hydropower Plants, which is composed of three generating units. The aim of this optimization process is to allocate the demand power for each unit from the total plant dispatched power, in order to obtain the maximum power plant efficiencies.

Power Plant Efficiency

The efficiency of each unit (η) is the electrical power output (P) to the hydraulic input power (P_h).

$$\eta = \frac{P_e}{P_h}$$

A second order polynomial is often used to represent the generated power efficiency behaviour, that is:

$$\eta = aP^2 + bP + c$$

Considering P_{ei} as the hydraulic power in the i-th turbine and η_G as the global efficiency, yields:

$$\eta_G = \frac{P_{e1} + P_{e2} \dots \dots P_{e(n-1)} + P_{en}}{P_{h1} + P_{h2} \dots \dots P_{h(n-1)} + P_{hn}}$$

Using above equation we can obtain:

$$\eta_G = \frac{P_{e1} + P_{e2} \dots \dots P_{e(n-1)} + P_{en}}{\frac{P_{e1}}{\eta_1} + \frac{P_{e2}}{\eta_2} \dots \dots \frac{P_{e(n-1)}}{\eta_{n-1}} + \frac{P_{en}}{\eta_n}}$$

where, η_i is the efficiency of the i-th unit.

From above two equations we can realize that η_G will result in different values depending on the allocation of the dispatched power among the n available units. For any dispatched power, there always will be one optimal power distribution among the available units to obtain the maximum global efficiency or, in other words, the global optimum.

The Offline Procedure

The aim of the optimization is to obtain a maximum global efficiency of the power plant through the optimal power allocation among the available units. In the off-line procedure, the solution of this problem is a mathematical use of non-linear mathematical programming developed in MS Excel with help of Solver. The knowledge of the efficiency curve of each unit has to be obtained from previous field tests. Therefore, the formulation of the optimization problem, including the objective function and the constraints is given by

$$\eta_G = \frac{P_{e1} + P_{e2} \dots \dots P_{e(n-1)} + P_{en}}{\frac{P_{e1}}{\eta_1} + \frac{P_{e2}}{\eta_2} \dots \dots \frac{P_{e(n-1)}}{\eta_{n-1}} + \frac{P_{en}}{\eta_n}}$$

$$\text{s.t.} \sum_{j=1}^{n} P_j = P_d$$

$$P_{jmax} \geq P_j \geq P_{jmin}$$

where, η_j and P_j are the efficiency and the delivered power of the j-th unit, respectively; P_d is the total dispatched power; and P_{jmin} and P_{jmax} represent the operating region of the j-th unit defined by its lower and upper generating power, respectively. It is considered in this model that the net head does not vary.

The Online Procedure

The online procedure is not based on a specific model, but on real time measurement of some important system variables that will be used in system optimization. Considering that models are simplified representations of the real world, certainly the results of online procedures will be often better than those obtained with offline procedures, because they are based on real-time and real world measurements. The real-time represents the periodical interventions of an agent on the system, in accordance with the available data at that measurement moment, which are applied until the convergence to a considered optimal value.

In the hydro power plant optimization, the load allocation between the available units is changed in a periodic way in accordance with the measurements variation, that could be efficiency, flow or pressure measurements. The great advantage of the online procedure is that its results will be better than the offline procedures, due to operational conditions and simplifications applied to the mathematical model used in the optimization process.

Optimization Using Efficiency Measurement

The optimization of the power generation must follow an objective function and some variables should be provided to the controller responsible for the units loading allocation. The necessary information is the individual power (P_j) and efficiency (η_j), and the dispatched power (P_d). The variable P_d must be provided only once and the variables P_j and η_j, must be provided by specific sensor devices, in real time, at an adequate update rate. The variable P_j can be provided to the system using specific device meters or digital relay outputs, while variable η_j must be obtained using specific device meters.

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:

$$P_h = g.H_N.\ Q$$

$$Q = P_h/(g.H_N)$$

Where, g is the gravitational constant (m/s²), Q is the input flow (m³/s), and H_N is the net head (m) obtained as the difference between the gross head and the friction losses in the hydraulic system.

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:

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

$$\text{s.t.} \sum_{j=1}^{n} P_j = P_d$$

$$P_{jmax} \geq P_j \geq P_{jmax}$$

where, Q_j is the input flow in the j-th unit, and Q_T 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 water energy, 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:

$$\eta_1 = 0.9474\ Q_1^3 - 2.8708\ Q_1^2 + 2.9368\ Q_1 - 0.0906 \quad (1.1)$$

$$\eta_2 = 0.9357\ Q_2^3 - 2.8713\ Q_2^2 + 2.9598\ Q_2 - 0.0937 \quad (1.2)$$

$$\eta_3 = 0.8352\ Q_3^3 - 2.6771\ Q_3^2 + 2.8494\ Q_3 - 0.0820 \quad (1.3)$$

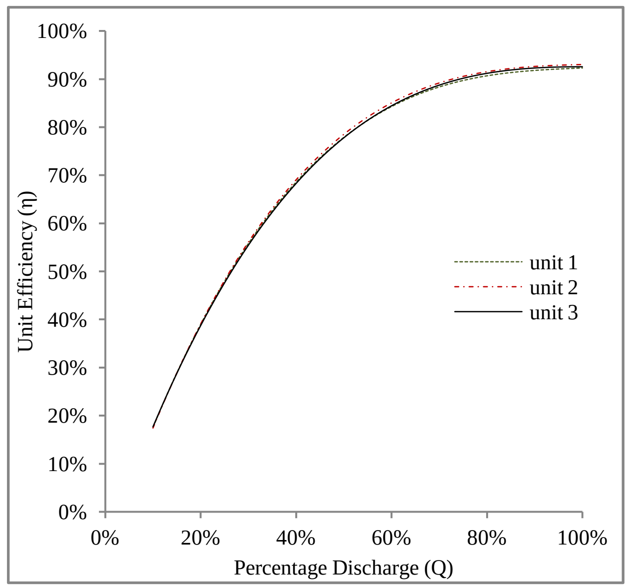

Figure 8: Efficiency Characteristics of Units

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

$$P_1 = 9.81 * 40 * Q_1 * \eta_1 \quad (1.4)$$

$$P_2 = 9.81 * 40 * Q_2 * \eta_2 \quad (1.5)$$

$$P_3 = 9.81 * 40 * Q_3 * \eta_3 \quad (1.6)$$

$$P_{total} = P_1 + P_2 + P_3 \quad (1.7)$$

Combining equations (1.1) to (1.7), we get,

$$P_{total} = 9.81 * 40 * (0.9474\ Q_1^4 - 2.8708\ Q_1^3 + 2.9368\ Q_1^2 - 0.0906\ Q_1 + 0.9357\ Q_2^4 - 2.8713\ Q_2^3 + 2.9598\ Q_2^2 - 0.0937\ Q_2 + 0.8352\ Q_3^4 - 2.6771\ Q_3^3 + 2.8494\ Q_3^2 - 0.0820\ Q_3) \quad (1.8)$$

Equation (1.8) 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:

$$Q_1, Q_2, Q_3 \leq 14.34\ m^3/s$$

$$\eta_1, \eta_2, \eta_3 \leq 100\%$$

This mathematical model represents actual physical behaviour of power production in DHPP.

An offline model for Type II optimization of unit commitment and discharge distribution for optimal power generation has been developed. This model has been verified using generation and discharge measurement of fiscal year 2068/69 and calculations have been done to find out the results that would have been gained if Type II optimization had been implemented.

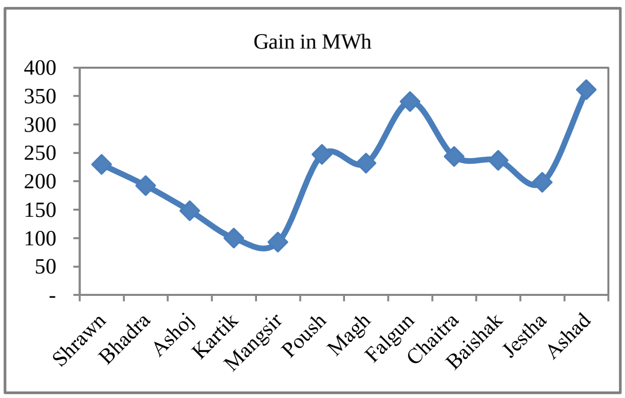

Figure 9: Monthly Gain (in MWh) for Type II Optimization

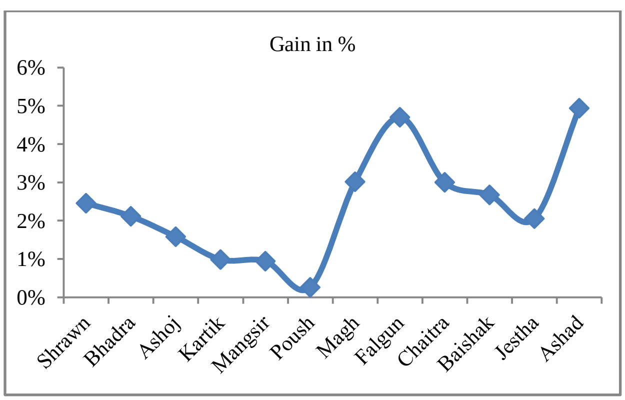

Figure 10: Monthly Gain (in percentage) for Type II Optimization

Figure 9 and figure 10 shows the optimized monthly gain trend along the year. Low discharge month had high gain indicating high optimization potential during low discharge period and high discharge month had low gain indicating low optimization potential but for the month of Ashad high gain for high river discharge period is due to the fact that two units of THPP were out of operation for 2068 Ashad, which resulted in low discharge for DHPP.

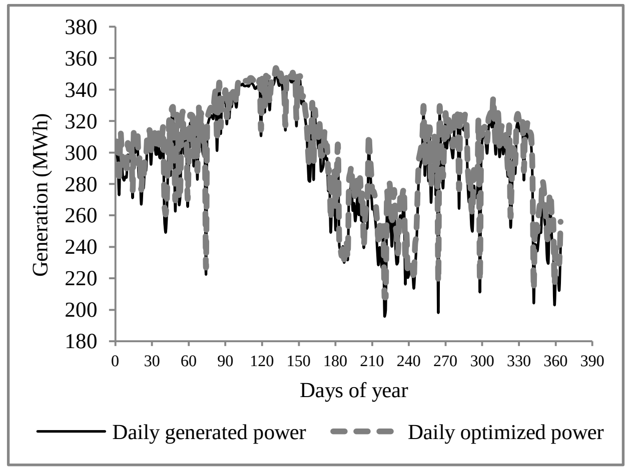

Figure 11: Comparison of daily generation before and after Type II Optimization

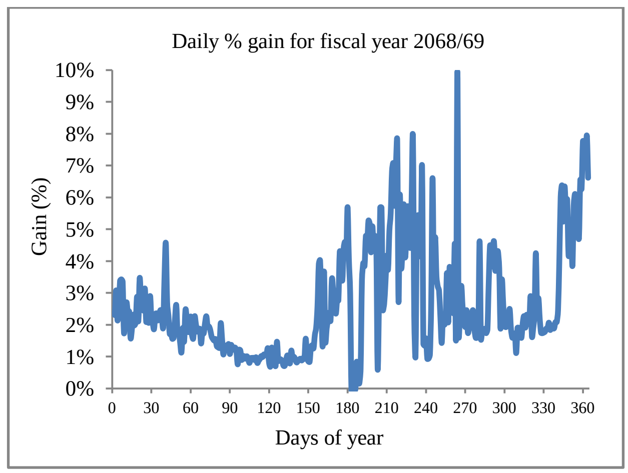

Figure 12: Daily gain (%) for a year under review

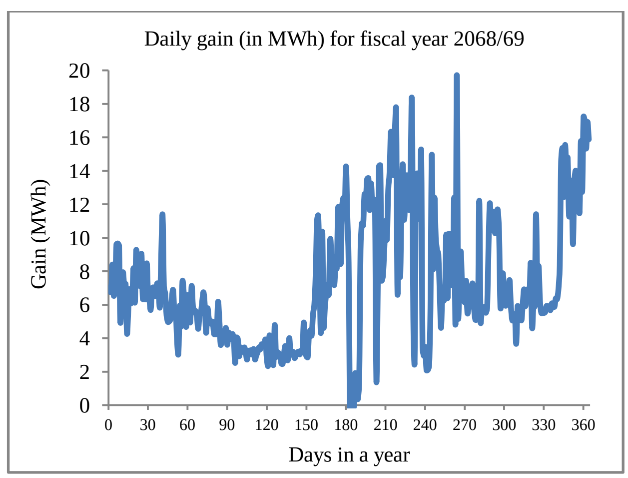

Figure 13: Daily gain (MWh) for a year under review

Figure 11, Figure 12 and Figure 13 indicate that there exists possibility of online Type II optimization in DHPP.

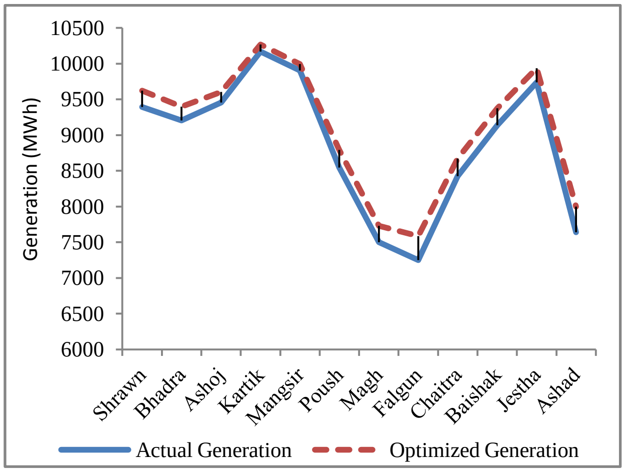

Figure 14: Monthly comparison between actual and optimized generation

Figure 14 proves that total generation from equal distribution of discharge between units is always less than the total generation by allocation of discharge to the units obtained from Type II optimization.

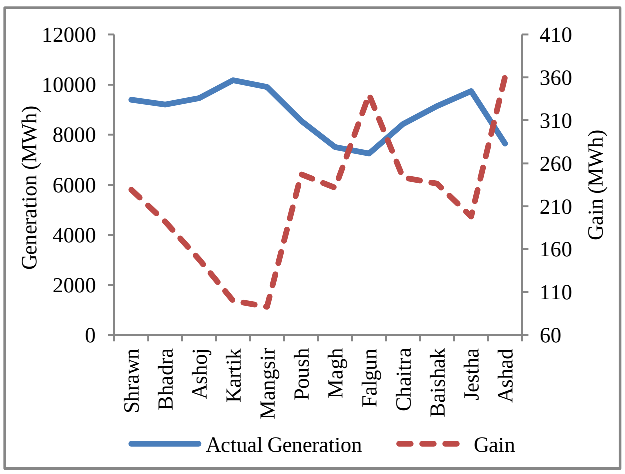

Figure 15: Monthly gain compared to actual generation

Figure 15 shows that during dry months or when discharge is low, gain is maximum. This is especially important as demand is high and overall generation is low during this period. So optimization is effective and relevant during dry months. In month of Ashad, even though flow in river is high, due to unit breakdown in THPP, DHPP received a reduced discharge which is responsible for low generation and high gain.

Comparison of daily actual and optimized power generation of Two representative months, one with most favourable condition for optimization (low discharge condition) month of Falgun and another with least favourable condition for optimization (high discharge with high head and clean water) month of Kartik are shown i Figure 16 to 19.

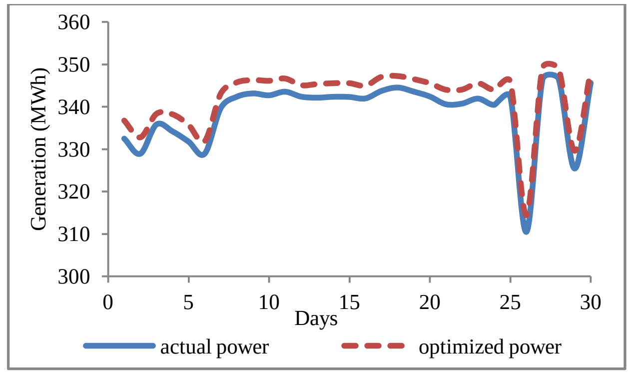

Figure 16: Comparison of daily actual and optimized power generation of Kartik

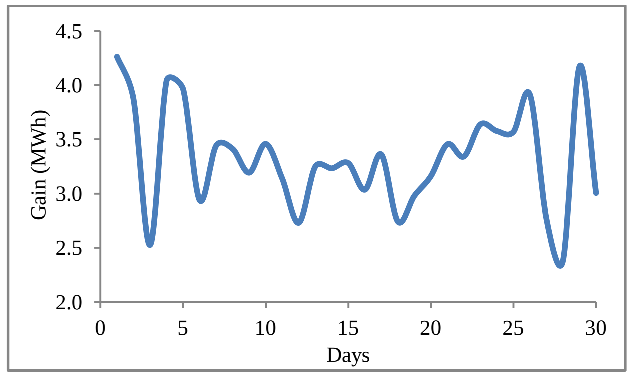

Figure 1: Daily gain of Kartik

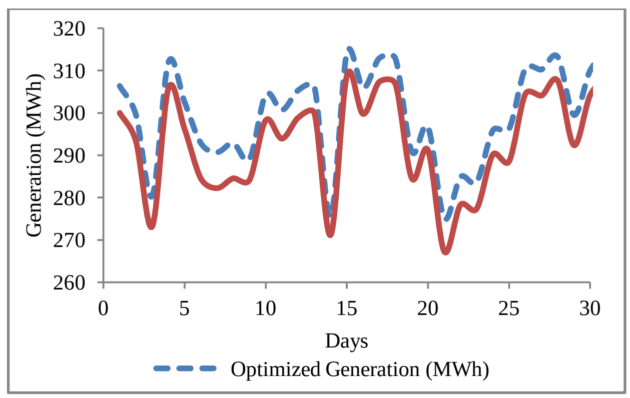

Figure 2: Comparison of daily actual and optimized power generation of Falgun

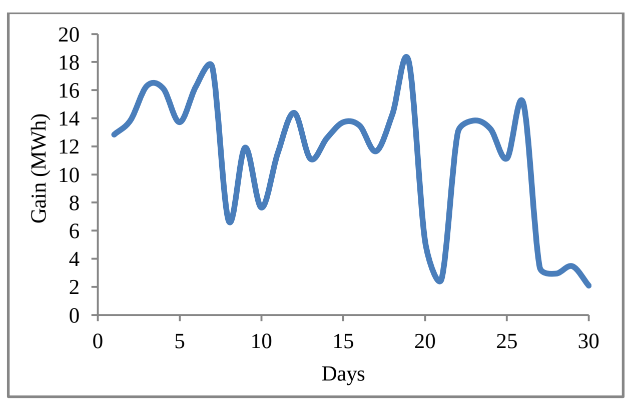

Figure 3: Daily gain of Falgun

Gain due to optimization during dry months compared to wet months is high which can be verified by comparing Figure 17 and Figure 19.

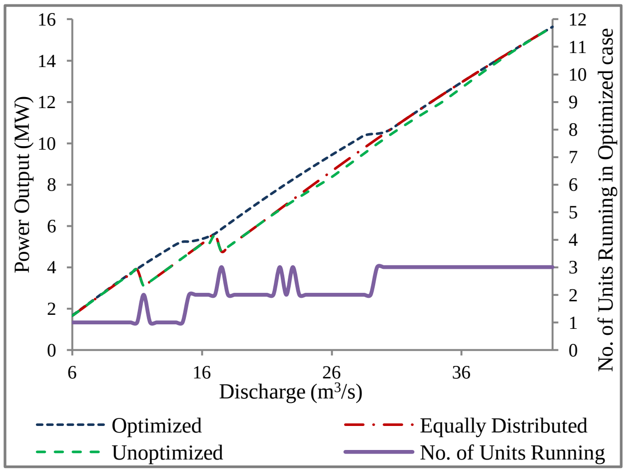

Figure 4: Comparison between different discharge distributions

Figure 20 compares power output from different modes of discharge distribution for different units in DHPP. For high value of discharge, variation in power output from all three modes of discharge distribution is quite low. But for medium and low discharge, power output from optimized distribution is significantly high. Moreover, equal distribution and un-optimized distribution (worst case distribution) result in similar power output. This indicates that for medium and low flow condition, conventional practice of equal distribution is not an effective way of power generation. After discharge of 29.5m^3/s, all three units are operating, so unit commitment is best applicable below this range of discharge.

4. CONCLUSION

The output from hydro power plant is function of net head, available discharge and unit's efficiency factor. For a pre-installed plant designed head and designed discharge can't be changed. Thus maximized output from pre-installed plant can be obtained by methods that enhance efficiency of units thus enhancing overall efficiency of hydro power plant.

Type I optimization helps to increase unit's efficiency by the process of overhauling or rehabilitation. Type II optimization enhances output by efficient unit commitment and loading.

Both Type I and Type II optimization help to enhance performance of units in a power plant resulting in better generation with better performance indices. By implementation of Type I optimization, output i.e. generation is increased due to enhancement of unit's efficiencies also Type I optimization helps to enhance performance indices of hydro power plant by increasing availability, reliability, capacity factor, load factor, plant utilization factor, MTBF and by decreasing forced outage rate, MTTR.

Implementation of Type II optimization output generation of hydro power plant helps to maximize output i.e. generation by optimal allocation of discharge between units.

Large amount of investment is required for Type I optimization with certain period of no power output. Hence, prior economic and financial analysis should be performed before committing for Type I optimization. Nevertheless, Type I optimization is capable of enhancing generation by reducing failures and improving performance characteristic of units.

Type II 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 II optimization is best suited for dry season (low discharge periods) when there is an acute deficit in energy supply in the system. For DHPP, Type II optimization can result in 2.62% (2619.33MWh) enhancement in generation which is equivalent to addition of 0.4MW plant in the system without any additional investment and environmental cost.

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