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Enhancement in Power Generation in Hydroelectric Power Plants with Water Conservation- A Case Study

Shambhu Ratan Awasthi*, Vishnu Prasad**, Saroj Rangnekar***
*(Department of Energy, Maulana Azad National Institute of Technology, Bhopal-51)
**(Department of Civil, Maulana Azad National Institute of Technology, Bhopal-51)
***(Department of Energy, Maulana Azad National Institute of Technology, Bhopal-51)

ABSTRACT
Today, importance of water is realized better than ever before. Awareness on making judicious and optimum use of water is continuously on the increase. The hydroelectric power plants need huge quantity of water for their operation. Normally these plants are operated as per the generation schedule provided by the Load Dispatch Centre. The method presented in this paper is based on the fact that discharge of water is minimum when a turbine operates at maximum efficiency, thus conserving water and thereby enhancing power generation as compared to normal or conventional practice. A case study for Indira Sagar Hydroelectric power plant is presented and estimated for other hydroelectric power plants in cascade on river Narmada in India.

***Keywords* -** Power generation, cascaded power plants, generation scheduling, water conservation, turbine efficiency.

I. INTRODUCTION

With the increasing population, availability of water is declining fast which is a matter of serious concern. In the last century, study of hydro power plants received little attention as there was no concept of cost of water. In the 21st century, optimum utilization of water in hydro power plants is drawing more attention of the researchers.

In the literature on generation scheduling of hydro power plants, it is found that all the hydraulic and electric losses in a power plant are not considered [1, 2, 3]. Start-ups and shut downs result not only in loss of water but also cause wear and tear leading to increased maintenance. The concept of additional cost due to start-ups in a hydroelectric power plant was presented [4, 5]. The process of start-ups and shut-downs is phased out and loss of water in these processes are mathematically modeled [6]. Polynomial functions of 2nd and 4th degree are used to model the efficiency of turbine-generator [7]. The difference in 2nd and 4th degree turbine-generator efficiency models is found to be very small. A pre-dispatch model is presented for hydroelectric power system that minimizes generation and transmission losses on an hourly basis throughout a day [1]. When applied to a hydroelectric power system in Brazil, significant savings are achieved as compared to normal operating practice. An was proposed for optimal use of water to be discharged by each hydroelectric power plant, in order to obtain optimal commitment of units [8]. The methodology aims minimum operation cost satisfying the constraints of forbidden operation zones. A method is presented to assess the cost of maintaining mandatory operating reserves in a single hydroelectric power plant in a Brazilian system [9]. It is costlier to operate generator at sub-optimal efficiency as compared to operation at maximum efficiency. A non-linear programming based model is proposed to solve short-term operation scheduling problem of a single hydropower plant with a small reservoir with an objective to maximize its revenues by [10]. It considers water discharge and reservoir volume and schedules start-ups/shut-downs to obtain unit commitment and dispatch of the committed units. In order to meet the load demand, the units of a hydroelectric power plant are to be operated at equal loads [11, 12, 13].

A non-linear approach to solve short term hydro scheduling problem is proposed [14] in a head sensitive cascaded hydro power system with an objective to maximize the profit in terms of water stored in reservoirs. The constraints included water balance, head, power generation, water storage, discharge and spillage. The case study is conducted on a Portuguese cascaded hydro power plants by linear as well as non-linear approach. The results obtained by both the methods are compared. The non-linear approach results in 4% more profit due to increased average storage in the reservoir by considering the effect of head variation.

One of the evolutionary methods, namely, Particle Swarm Optimisation and its variants [15, 16] are used successfully in dealing with the problem of generation scheduling of hydroelectric power plants. Optimum hourly generation scheduling is obtained using Time Varying Acceleration Coefficients Particle Swarm Optimisation method [3, 16] in cascaded hydroelectric power plants with an objective to minimize the gap between load demand and generation in a system with equality and inequality constraints pertaining to hydraulic and generation parameters. The methodology is tried on hydroelectric power plants on Narmada river in India. The results show superior dynamic convergence characteristics as compared to one obtained by Novel Self Adaptive Inertia Weight method.

A long term fuzzy based dynamic programming model is proposed [17] to solve the optimization problem of cascaded hydropower plants. This is applicable as a single objective or multi-objectives model. The methodology is applied on Three Gorges cascaded multifunctional reservoir to maximize power generation of Three Gorges Hydro electric project and minimize surplus water of Gezhouba. The fuzzy based dynamic programming proved to be more convenient and faster than ordinary dynamic programming. The authors suggest that for higher precision, level of the reservoirs can be divided into more parts, though it may result in the 'curse of dimensionality'. This problem can be overcome by replacing dynamic programming with some intelligent algorithm like Particle Swarm Optimisation, preferably fuzzy based.

A Grouping Differential Evolution (GDE) algorithm is applied [18] to solve complex optimal scheduling of cascaded hydroelectric power plants with an objective to maximize total generated energy meeting the constraints of reservoir balance, power output, water level and discharge limits. The methodology is applied to Three Gorges cascaded hydro power project, China. GDE algorithm is found to be more efficient than dynamic programming and capable of getting rid of local maxima as well as avoiding premature convergence.

Ideally, generating units should be operated at maximum turbine efficiency to meet the load demand. If it is not possible to do so, then this paper presents a new technique of dividing total number of operating units in two groups. The units in one group operate at maximum turbine efficiency whereas one or more units in the other group operate at sub-optimal turbine efficiencies. The main features of the developed algorithm are demonstrated by applying to a 8x125 MW Indira Sagar Hydroelectric Power Plant on Narmada river in India. In this technique, enhancement in generation with conserved water is computed. For other projects in cascade, enhancement in generation is estimated assuming water conservation to be in the same proportion as in the case of Indira Sagar Project. The computer program developed for Indira Sagar project is project specific. It is coded in MATLAB and run on a core 2 duo, 2.1 GHz, 4 GB RAM system.

The paper presents formulation of problem for flow optimization, application of the proposed methodology to a working power plant and computation of enhanced generation with conserved water. For other power plants in cascade, enhanced generation is estimated. Finally the conclusions of the work are drawn.

II. PROBLEM FORMULATION AND OPTIMISATION

The objective function is taken as :

$$min \sum_{i=1}^{m} Q_i$$

where Q_i = discharge of i^{th} unit
m = number of units in operation

2.1 Constraints

Equality constraint

Power balance :

Load dispatch = Generator output + electrical losses upto switchyard

Inequality constraint

$m \leq n$

2.2 *Bounds*

Reservoir elevation : $MDDL \geq H_{lh} \leq FRL$
Turbine discharge : $Q_{min} < Q < Q_{max}$
Unit output : $P_{min} < P_{geach} < P_{max}$
Head : $H_{min} < H < H_{max}$

Efficiency of turbine is obtained from hill curves of a prototype. Variation of turbine efficiency with head and power output for Indira Sagar Project is shown in Fig. 1.

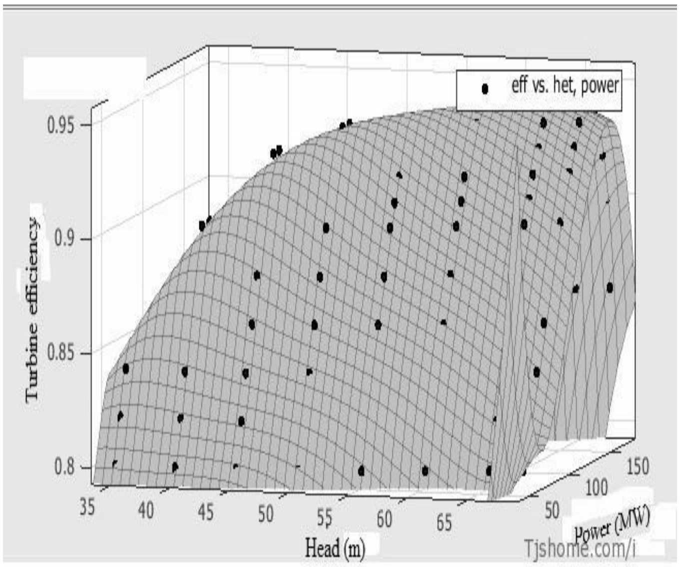

Figure 1. Hill curves of a prototype

Operation of a turbine at maximum turbine efficiency results in minimum requirement of water. Variation in maximum turbine efficiency with head for Indira Sagar Project is shown in Fig. 2.

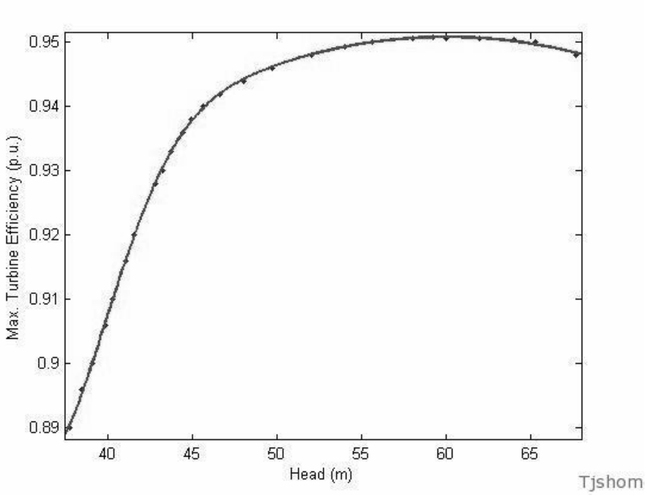

Figure 2. Variation in maximum turbine efficiency with head

III. APPLICATION TO A HYDROELECTRIC POWER PLANT

The coefficients required for various equations in the proposed methodology are computed for 8x125 MW Indira Sagar Hydroelectric power plant for its optimal generation scheduling. The power plant is built on a 1312 km long interstate river Narmada in the state of Madhya Pradesh in India. The reservoir of project is the largest in India with gross storage capacity of 12.22 billion m^3, surface area of 913 km^2 at full reservoir level and catchment area of 61,642 km^2. The full reservoir elevation of the reservoir is 262.13 m whereas minimum draw down level is 243.23 m. The power plant is equipped with Francis turbines with a rated head of 60 m and a discharge of 229.5 cumecs. The generating units are designed for 10% continuous overload operation.

The loading of the units in a power plant depends on the load demand while the head on turbines depends on the water level in the reservoir. Hence, the numerical computations have been performed for following two cases :

- Constant load to minimize discharge
- Constant head to maximize generation

3.1 Constant load

The total capacity of the power plant is 1000 MW. However, for the purpose of computations, average constant load of 700 MW is considered. The electrical losses from generator terminals to switchyard are taken as 0.3% based on power plant data, the generator output required is 702.1 MW. The plant discharges for optimized combinations of units at different heads from MDDL to FRL are computed and given in Table I.

Table 1. Optimized Combination of Units and Plant Discharges

Reservoir elevation (m)	Units at maximum turbine efficiency			Units at sub-optimal turbine efficiency		
	Gen. output (MW)	Maximum Turbine efficiency	Discharge (cumecs)	Gen. Output (MW)	Turbine efficiency	Discharge (cumecs)
243.23	---	0.9414	---	8x87.7	0.9274	8x212.0
245.0	6x101.2	0.9445	6x230.7	1x94.6	0.9300	1x218.5
250.0	5x113.6	0.9489	5x232.4	1x82.0+1x 51.9	0.8847 0.8133	1x180.3 1x125.1
255.0	5x125.9	0.9507	5x234.3	1x72.6	0.8500	1x151.3
260.0	4x137.5	0.9502	4x236.4	2x75.95	0.83685	2x148.1
262.13	4x137.5	0.9493	4x237.5	2x75.95	0.825	2x145.27

The plant discharges obtained for equal load operation are given in Table 2.

Table 2. Operation with Units at Equal Loads

Reservoir elevation (m)	Head (m)	Generator Output (MW)	Turbine efficiency	Plant discharge (cumecs)
243.23	46.346	8x87.7	0.9274	1696.0
245.0	48.210	7x100.3	0.9292	1626.4
250.0	53.426	7x100.3	0.9213	1480.2
255.0	58.593	6x117	0.9096	1366.8
260.0	63.722	6x117	0.8842	1292.8
262.13	65.897	6x117	0.8736	1265.3

It is seen from Tables 1 and 2 that discharge required in Table-2 is less than that in Table-1 except at reservoir elevation of 243.23 m. The saving in discharge and enhancement in power output at different heads is given in Table 3.

Table 3. Enhanced Generation with Conserved Water

Reservoir elevation (m)	Optimised plant discharge (cumecs) (Table I)	Plant discharge with equal loads (cumecs) (Table II)	Saving in discharge	Enhancement in power
			(cumecs)	MW
243.23	---	1696.0	0.0	0.0
245.0	1602.6	1626.4	23.8	9.1
250.0	1467.5	1480.2	12.7	5.39
255.0	1322.9	1366.8	44.0	20.38

260.0	1242.0	1292.8	50.84	25.64
262.13	1240.5	1265.3	24.87	12.97

It is observed from Table 3 that saving in discharge does not follow a regular pattern it but varies with head. Discharge is minimum at maximum turbine efficiency. It depends on the deviation of the unit(s) operating at sub-optimal turbine efficiency from maximum turbine efficiency. At each head there is a maximum output limit. The output available around rated and higher heads is quite high but a generating unit is operated within design output limit as well as maximum output limit. Variation in enhancement in power with the head variation from MDDL to FRL is shown in Fig. 3.

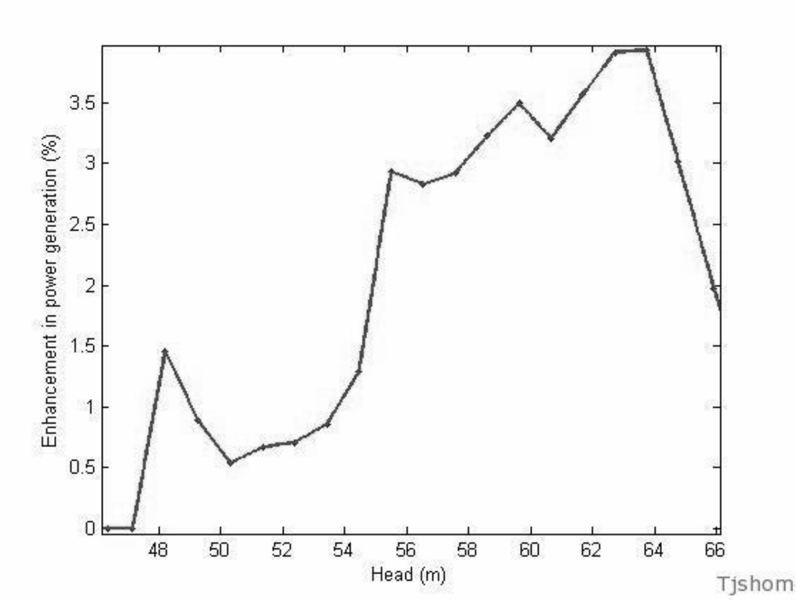

Figure 3. Variation in enhanced generation with head

3.2 Constant head

In this case, an average head of 55 m is taken as constant head. The maximum turbine efficiency at 55 m head is 0.9497. Load demand is varied and taken at 40%, 50%, 60%, 70%, 80% and 90% of rated plant output. The plant discharges for optimized combination of units at different loads are computed and given in Table 4.

Table 4. Optimized Combination of Units at Constant Head

Load demand (MW)	Units at maximum turbine efficiency			Units at sub-optimal turbine efficiency		
	Gen. output (MW)	Maximum turbine efficiency	Discharge (cumecs)	Gen. Output (MW)	Turbine efficiency	Discharge (cumecs)
400	3x117.3	0.9497	3x233.0	1x49.2	0.790	1x118.4
500	3x117.3	0.9497	3x233.0	1x54.4, 1x95.1	0.8156, 0.9037	1x126.8, 1x198.6
600	4x117.3	0.9497	4x233.0	2x66.18	0.8494	2x147.6
700	5x117.3	0.9497	5x233.0	2x57.65	0.8272	2x132.3
800	6x117.3	0.9497	6x233.0	1x98.1	0.9092	1x203.7
900	7x117.3	0.9497	7x233.0	1x81.0	0.8770	1x174.5

The plant discharges obtained for equal load operation are given in Table 5

.

Table 5. Operation with Equal Loading of Units

Load	Power loss	Total	Nos. x Output	Turbine	Plant

demand (MW)	from generator terminals to switchyard (MW)	generated output (MW)	of each generator (MW)	Efficiency	discharge (cumecs)
400	1.2	401.2	4x100.3	0.9128	829.5
500	1.5	501.5	5x100.3	0.9128	1036.8
600	1.8	601.8	6x100.3	0.9128	1244.1
700	2.1	702.1	7x100.3	0.9128	1451.3
800	2.4	802.4	7x114.6	0.9210	1643.4
900	2.7	902.7	8x112.8	0.9223	1846.1

From Table 4 and 5, two sets of plant discharges are available for each reservoir elevation. Saving in discharges are computed and given in Table 6.

Table 6. Enhanced Generation with Conserved Water at Constant Head

Load demand (MW)	Optimised plant discharge (cumecs) (Table IV)	Plant discharge with equally loaded units (cumecs) (Table V)	Saving in discharge	Enhancement in power
			(cumecs)	MW
400	815.4	829.50	12.10	5.27
500	1024.3	1036.8	12.49	5.44
600	1227.1	1244.1	16.95	7.38
700	1429.5	1451.3	21.80	9.49
800	1601.6	1643.4	41.74	18.17
900	1805.4	1846.1	40.70	17.71

It can be seen from Table 6 that saving in discharge is maximum at load demands of 800 and 900 MW which correspond to maximum turbine efficiencies. Similarly, at load demands of 400 and 500 MW, turbine efficiencies as well as saving in discharges are low. Variation in enhancement in generation with load is shown in Fig. 4.

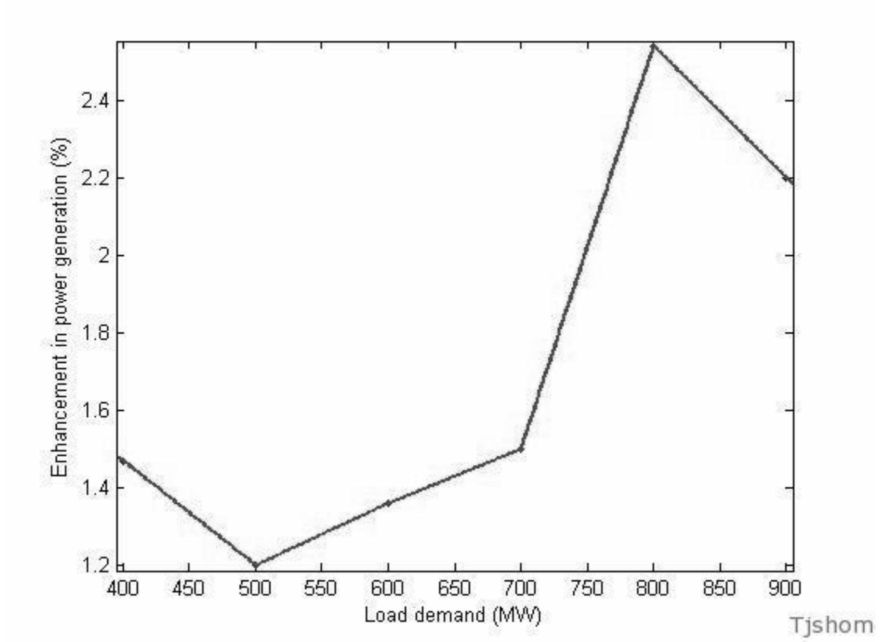

Figure 4. Variation in enhanced generation with load

IV. APPLICATION TO CASCADED HYDROELECTRIC POWER PLANTS

Various projects in cascade on river Narmada and their hydraulic parameters are given in Table 7.

Table 7. Hydroelectric Projects in Cascade on Narmada River

Project	Rated output (MW)	Type of turbine	Rated head (m)	Rated discharge (cumecs)	Full Reservoir Level (m)	MDDL (m)	Max. Tail water level (m)	Min. Tail water level (m)
Rani Avantibai Sagar	2x45	Francis	47.85	107	422.76	403.98	370.88	369.05
Indira Sagar	8x125	Francis	60.0	229	262.13	243.23	196.6	193.54
Omkareshwar	8x65	Francis	32	237.25	196.6	193.54	162.76	162.2
Maheshwar	10x40	Kaplan	20.78	230	162.76	162.2	142.9	140.5
Sardar Sarovar River bed	6x200	Reversible Francis	96	204.9	138.68	110.64	26.0	19.0
Sardar Sarovar Canal	5x50	Kaplan	36	157.6	138.68	110.64	95.1	92.07

By applying the proposed methodology, enhancement in power is computed for 8x125 MW Indira Sagar Project. For a constant load of 700 MW, enhancement in power with conserved water is upto 3.91% with an average of 2.07% as shown in Figure 3. In case of a constant average head of 55 m, water conservation is upto 2.54% with an average of 1.71% as shown in Figure 4.

The computer program is project specific and is developed for Indira Sagar Hydroelectric Project. Saving in other projects in cascade on river Narmada can be worked out from respective performance curves of turbine/generator and power plant data. In this paper, other projects in cascade and equipped with Francis turbines are assumed to follow the proposed methodology and conserve water in the same proportion. On this assumption, enhanced generation capacity of the projects in cascade is worked out. The projects equipped with Kaplan turbines are ignored because water conserved in Kaplan turbines is small as their efficiency curves are quite flat due to dual regulation of water flow. In view of this, water conservation in Maheshwar and Sadar Sarovar Canal projects are not taken into consideration. Enhanced generation capacity for the projects in cascade at constant load and average head are shown in Table 8.

Table 8. Estimated enhancement in generation capacity in the projects in cascade

Project	Rated output (MW)	Type of turbine	Enhancement in generation capacity (MW)	
			Average 2.07% at constant load	Average 1.71% at constant head
Rani Avantibai Sagar	2x45	Francis	1.9	1.5
Indira Sagar	8x125	Francis	20.7	17.1
Omkareshwar	8x65	Francis	10.8	8.9
Maheshwar	10x40	Kaplan	Saving, not considered	Saving, not considered
Sardar Sarovar River bed	6x200	Reversible Francis	24.8	20.5
Sardar Sarovar Canal	5x50	Kaplan	Saving, not considered	Saving, not considered
		TOTAL	58.2 MW	48 MW

V. CONCLUSION

An algorithm has been developed for minimization of plant discharge. The enhanced average generation of 2.07% and 1.71% respectively are achieved for constant load and constant head in 8x125 MW Indira Sagar hydroelectric plant. Total enhancement in generation is found to be 58.2 MW in constant load variant whereas 48 MW in the case of a constant head. The enhanced generation capacity for other cascaded power plants on river Narmada are found to vary from 1.5 to 24.8 MW.

Availability of such inputs will enable utilities to coordinate with river regulatory authority and Load Dispatch Centre for generation scheduling with optimized flow. Enhanced generation from the same quantity of water will reduce dependency to some extent on fossil fuels based power which is mainly responsible for emissions of green house gases and in-turn global warming. In summer, water levels in reservoirs are low but demand of electricity is high. Such a situation necessitates meticulous water management. Enhancement in power generation with conserved water is significant. Another advantage of operation at maximum turbine efficiency is the smooth operation of turbines from the point of view of vibrations and cavitation which reduces maintenance time and cost.

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