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Optimal Reservoir Operation for Hydropower Generation

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Abstract : Hydropower is one of the vital components of reservoir operation, especially in large multi-purpose reservoirs. It is a renewable, economic, non-polluting and environmental friendly source of energy. India is endowed with enormous economically exploitable and viable hydropower potential. However, only 15% of the hydroelectric potential has been harnessed so far and 7% is under various stages of development. Optimizing the reservoirs serving hydropower and irrigation are complex, since they are having conflicting objectives, if power production is not incidental. In the present study, the Koyna reservoir operation is optimized for hydropower production and irrigation using non-linear programming technique. The Koyna Hydroelectric Power project is having four stages with a total capacity of 1920 MW. In this study, it is found that there is a possible power production of 2665 x 10^6 kWh. The developed model has also resulted in good storage at the end of the season to meet the unprecedented demand. The study shows that Koyna reservoir is having more potential to generate more hydropower.

Keywords: Hydropower generation, Optimization, non-linear programming, Koyna Hydroelectric Project

INTRODUCTION

Hydropower is one of the potential sources for meeting the growing energy needs of a country. The main advantages of hydropower are the absence of pollution during operation, its capability to respond quickly to changing utility load demands, and its relatively low operating costs. India is endowed with rich hydropower potential and it ranks fifth in the world in terms of usable potential. In India, most of the reservoirs have hydropower plants. However, less than 25% has been developed or taken up for development (ADB, 2007) and the existing hydropower plants are not operated to its full potential due to several reasons. Some of them are (i) in most of the plants, hydropower is produced through irrigation release; (ii) hydropower and irrigation are conflicting objectives. Hydropower requires more head to be available in reservoir for efficient operation where as crop production requires more release for irrigation. As per ADB (2007) report, nearly 78% of the potential remains without any plan for exploitation. Thus in the present scenario, there is a need to exploit and optimize the existing hydropower plants for optimal hydropower generation combined with irrigation. This calls for an efficient and effective operation of reservoirs for the development of the country in agricultural as well as power sector.

Several studies have been reported in optimizing the reservoir operations using various techniques like linear programming (LP), non-linear programming (NLP), goal programing (GP), chance constraint linear programming (CCLP), dynamic programming (DP) and recently, soft computing techniques. Even though various techniques are available, the complexity of the model depends on the case study and its associate problems. Simonovic and Srinivasan (1993) developed a reliability model for optimizing the operations of a multipurpose reservoir for hydropower generation and flood control. The stochastic nature of reservoir inflow is incorporated in the model using cumulative probability functions. Arnold et al. (1994) developed an Augmented Price Method (APM) and Sequential Quadratic Programming

(SQP) models for optimizing a large scale hydropower plant in Zambezi river system, Africa. Both the algorithms were applied for different time horizons and inflow records.

Most of the hydrological processes are uncertain in nature which can be accounted in the model by considering as chance constraint. Sreenivasan and Vedula (1996) developed a chance constrained linear programming (CCLP) model for optimal operation of a multipurpose reservoir. The model maximizes the annual hydropower while meeting the irrigation demand for a specified reliability level. The chance constrained releases were converted into its deterministic equivalent using a linear decision rule and inflow probability distribution. It was reported that the maximum possible reliability for meeting the irrigation demand was 0.65 and the corresponding maximum annual hydro power produced by the bed turbine was 5.68 M kWh. Yi (1998) developed a Mixed Integer Programming (MIP) and applied to Lower Colorado River Basin to evaluate the capabilities of the optimal basin wide scheduling of hydropower units. It was reported that the developed MIP model resulted in increased revenue of about 3.08 million dollars per year. Peng and Buras (2000) developed optimal operation policies for a hydropower system, which consists of nine reservoirs in Maine, USA using a nonlinear programming technique. By generating synthetic inflows, the expected values and probability distribution of decision variables were estimated and analyzed.

Zahraie and Karamouz (2004) developed a time decomposition approach, which consists of monthly, weekly and hourly models for optimizing hydropower reservoirs in Iran. The Demand Driven Stochastic Dynamic Programming Model (DDSP) was applied for optimizing the operation of two hydropower reservoirs for long and midterm planning. It was reported that the DDSP optimal policies produced a 10 percent larger power generation than the historical records and more than 97 percent of the water demands were supplied. Devamane et al. (2006) developed a NLP model for a multi-reservoir system in upper Krishna basin for maximizing the irrigation, municipal and industrial releases and hydropower production. On comparing the results with the LP model, it was reported that the NLP model resulted in less irrigation deficit with more hydropower production. A non-linear multi-objective optimization model was developed by Moosavian et al. (2008) to optimize the annual scheduling of power generation in serial or parallel hydropower plants. The multiple objectives were converted to single objective using weighted-sum method. Then the power generation and water consumption were optimized by SQP for deriving rule curves for dry, medium and wet scenarios. It was reported that the amount of energy production increases with amount of random inflows, so a higher energy production is expected in wet scenario.

Bosona and Gebresenbet (2010) used Powersim Simulation software to model the Melka Wakana Hydropower Plant in Ethiopia. After developing and calibrating the model, the simulation analysis was carried out by controlling reservoir releases for energy production. It was reported that the results of the simulation analyses indicated that the yearly energy production was increased by 5.67% while evaporation loss was reduced by 38.33%. Reservoirs are needed to be optimized for effective, efficient and economical management and operation of various purposes. Among the various purposes of a reservoir, hydropower generation is crucial. From the literature review, it is found that the hydropower plants play a significant role in supplying the higher valued peak loads considering the hourly variations of the electrical load and the limitations of thermal units for short term changes in generation. Therefore, operational planning for hydropower reservoirs is more focused on peak generation. Thus, it very much essential to optimize the operation reservoir for hydropower production in accordance with irrigation. Hence, in the present study it is aimed to optimize the hydropower generation of large scale hydropower plant using NLP technique.

STUDY AREA

The Koyna Hydro Electric Project is considered as the case study. The Koyna Hydropower project is the lifeline of Maharashtra, which has four stages. The Koyna reservoir situated on the west coast of Maharashtra, India, alone has three powerhouses, two on western side and one on eastern side. The location of Koyna powerhouses is shown in Fig. 1. The Koyna stage – I was the first base load hydel station with 4 x 60 MW installation, later it was strengthened to 4 x 65. The second stage was designed to harness the capacity of 4 x 75 MW with the same head works as such, the dam, headrace tunnel, surge well pressure shafts and tailrace are common for these two stages. Thus, the combined total capacity of both the stage I and II is 560 MW (hereafter Stage I & II is referred as PH I). The full installed capacity of all the powerhouses supplying base power in the grid is not sufficient to cope up with the peak demand of Maharashtra during morning and evening peak hours of every day. Hence, it was decided to meet the demand during peak hours by converting the hydropower stations into peaking stations. This has given rise to Stage – IV (hereafter referred as PH II) with a capacity of 4 x 250 MW in Koyna Hydro Electric Project. Apart from power generation, there is also a need to release for irrigation and downstream riparian rights on eastern side, which has fertile land as compared to barron exposed rock covers, and undulating terrain on western side. Hence, the Koyna Dam Power House (KDPH) (hereafter referred as PH III) was constructed with a capacity of 2 x 20 MW to generated hydropower through irrigation releases. The Stage III is at Kolkewadi dam with a capacity of 4 x 80 MW. All the releases required for this Stage III is made from Kolkewadi dam and in turn, it is the tailrace water from PH I and PH II. Hence, the stage III is not considered in the present study. Thus, the total installed capacity of Koyna dam alone is 1600 MW (PH I, PH II and PH III). As stated, earlier the power production at Koyna dam is not continuous, since they are all peaking stations. They are operated only during the peak hours i.e. during the morning and evening where there is a peak demand. It is also to be noted that the power generation at PH III is incidental, since it is through irrigation release.

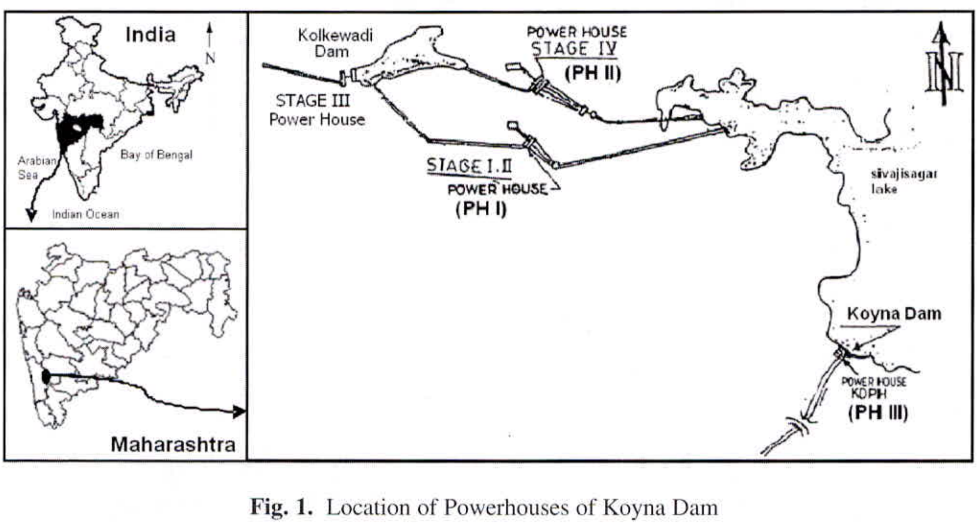

Fig. 1. Location of Powerhouses of Koyna Dam

MODEL FORMULATION

The power capacity of a hydropower plant is primarily the function of the hydraulic head and the flow rate through the turbines. According to Loucks et al. (1981), the hydropower production during any time period '*t*' for any particular reservoir is dependent on the installed plant capacity, flow through the turbines, average effective storage head, number of hours operation, plant factor (the fraction of time that energy is produced) and a constant for converting the product of flow, head and plant efficiency to electrical energy. Thus the hydropower produced (PH_t) in terms of kilowatt-hours (kWh) during the period '*t*' is expressed as

$$PH_t = 2725 \times R_t \times H_t \times \eta \quad t = 1, 2, \ldots 12 \quad (1)$$

Where R_t is the release to powerhouse during the time period '*t*', H_t is the net head available during the time period '*t*' and η is the plant efficiency. The average head available during a particular time period '*t*' is expressed as function of storage. Then the net head is estimated by deducting the tail water level and the frictional losses.

The objective of the study is to maximize the power production from the three powerhouses. It is expressed as

$$\text{Max } Z = \sum_{t=1}^{12} \sum_{n=1}^{3} PH_{n,t} \quad (2)$$

where, $PH_{n,t}$ is the power produced from the power house '*n*' during the time period '*t*' in terms of kilo Watt hour (kWh). The above objective function is solved subjected to various constraints. For any given time period '*t*', the final storage in the reservoir should be equal to the inflow, inflow, releases and other losses of the system. This is given as

$$S_{(t+1)} = S_t + I_t - \sum_{n=1}^{3} R_{n,t} - O_t - E_t \quad t = 1, 2, \ldots 12, n=1,2,3 \quad (3)$$

where, $S_{(t+1)}$ is the final storage in the reservoir during the time period '*t*' (10^6 m^3); S_t is the initial storage in the reservoir during the time period '*t*' (10^6 m^3); I_t is the inflow into the reservoir during the time period '*t*'(10^6 m^3); $R_{n,t}$ is the release to the powerhouse '*n*' during the time period '*t*' (10^6 m^3); O_t is the overflow from the reservoir during the time period '*t*'(10^6 m^3) and E_t is the evaporation losses from the reservoir during the time period '*t*', (10^6 m^3). The evaporation loss (E_t) during the period '*t*' is expressed as a function of initial and final storage during that particular time period. This is expressed as

$$E_t = a_t + b_t \left(\frac{S_t + S_{(t+1)}}{2} \right) t = 1, 2, \ldots\ldots 12 \quad (4)$$

Where, a_t is the constant and b_t is the slope of the straight line with water surface area plotted against reservoir storage. The power production during any particular time period '*t*' should be less than or equal to the maximum generating capacity of the plant

$$PH_t \le Pmax_{n,t} \quad t = 1, 2, \ldots 12; n = 1,2,3 \quad (5)$$

Where PH_t is the power produced in the powerhouse '*n*' during the time period '*t*'; $Pmax_{n,t}$ is the maximum capacity of generation for the powerhouse '*n*' during the time period '*t*'. The head available in the reservoir should be greater than the minimum draw down level of the powerhouse. This is expressed as

$$H_t \ge MDDL_{n,t} \quad t = 1, 2, \ldots 12; n = 1,2,3 \quad (6)$$

The diversion of huge quantity of water to the western side for power production has resulted in dispute. To ensure adequate water for irrigation on eastern side and other downstream disputes, the westward diversion was restricted to certain limit. Therefore, diversion of large quantity of water to westward for power production was restricted to 1912 x 10^6 m^3 (67.5 TMC). The total release for irrigation should be 849 x 10^6 m^3 (30 TMC).

$$\sum_{t=1}^{12} (R_{1,t} + R_{2,t}) \le R_{w,max} \quad t = 1, 2, \ldots 12 \qquad (7)$$

$$\sum_{t=1}^{12} R_{3,t} \le ID_{max} \quad t = 1, 2, \ldots 12 \qquad (8)$$

where, $R_{w,max}$ is the maximum water that can be diverted to the western side for power production and ID_t is the maximum water that can be released for irrigation (as per tribunal). The reservoir storage 'S_t' during any time period 't' should not be less than the minimum storage (S_{min}) or dead storage and should not be more than maximum storage (S_{max}) or capacity of the reservoir. This can be given by

$$S_{min} \le S_t \le S_{max} \quad t = 1, 2, \ldots 12 \qquad (9)$$

The overflow occurs when the final storage exceeds the reservoir capacity. This overflow constraint is given by

$$O_t = S_{(t+1)} - S_{max} \quad t = 1, 2, \ldots\ldots 12 \qquad (10)$$

$$\text{and } O_t \ge 0 \quad t = 1, 2, \ldots\ldots 12 \qquad (11)$$

where, S_{max} is the capacity of the reservoir during time period 't' (10^6 m^3) and $S_{(t+1)}$ is the final storage in the reservoir during time period 't' (10^6 m^3). This final storage is initial storage for the next time period '$t+1$', when there is no overflow. If overflow occurs then S_{max} will be the initial storage for the next time period '$t+1$' for the reservoir.

RESULTS AND DISCUSSION

In the present study, the hydropower houses of Koyna reservoir are optimized using a monthly time stepped non-linear programming technique. The above formulated non-linear programming model with 145 variables and 291 constraints is solved using GAMS/MINOS solver (GAMS, 2010). GAMS/MINOS solves the non-linear objective function problems using a reduced gradient algorithm combined with a quasi-Newton algorithm (GAMS, 2010). The model has been optimized using 75 percent dependable inflow, in which it is observed that the reservoir receives 90% of inflow during the monsoon period (5 months) and the remaining 10% during the non-monsoon period (7 months). Thus, the reservoir is completely dependent on monsoon rainfall only. Therefore it very much important to store the water to meet the unexpected demands during the non-monsoon periods. Hence, in actual the reservoir is always maintained with good storage.

The NLP model results show that the model has completely satisfies all the constraints. The model has resulted in an annual power production of 2665 x 10^6 kWh of hydropower. The resulted annual power production is slightly lesser than the actual, since in actual the westward release constraint is slightly violated due to peak demand where as the model strictly restricted the releases on the western side exactly to 1912 x 10^6 m^3. On the other hand the final storage in the reservoir shows that their still potential to generated more power. The resulted releases from the model for the PH I, PH II and PH III is shown in Fig. 2. From the figure, it can be seen that during the initial period of the season, the model has resulted in high releases, which shows that the inflow is high. During the non-monsoon season the release to the PH I and PH II are almost equal. It can also be observed that the irrigation release is higher than the powerhouse releases, which indicated that crop water requirement is more during the non-monsoon season. It is to be noted that all the irrigation releases are made through the PH III.

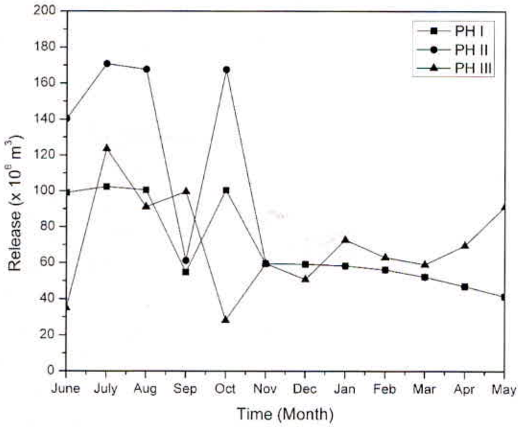

Fig. 2. Resulted releases from the NLP model

The resulted monthly power production at various powerhouses is given in Fig. 3. From the figure, it can be seen that the monthly power production for PH II is higher than PH I and PH III. This is due to that the capacity of PH II is higher than PH I and PH III. Even a less release to these powerhouses will generate more power since, the PH I and PH II are having high net heads. Also, the minimum drawdown level of PH II is higher than PH I and PH III. Thus, the reservoir is always maintained at higher level.

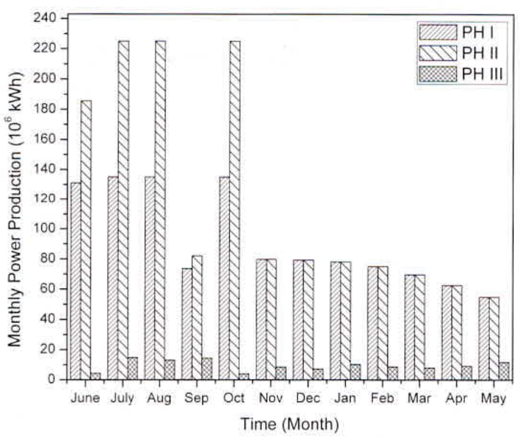

Fig. 3. Resulted monthly power production at various powerhouses

The final storage resulted from the model is shown in the Fig. 4. From the figure, it can be seen that during monsoon periods, the reservoir is almost full due to high inflow and the storage recedes during the non-monsoon period which has less inflow and more demand. It is also observed that the model has resulted more than 1600 x 10^6 m^3 storage for all the months, including the non-monsoon periods. It is due to the power production requires more head to be available in the reservoir and hence the model resulted in good end month storage. In reality also the reservoir is maintained with more storage throughout the year to meet unprecedented power demand. This is also shows that there is still potential to generate more power with the available storage. The evaporation is expressed as a function of the initial

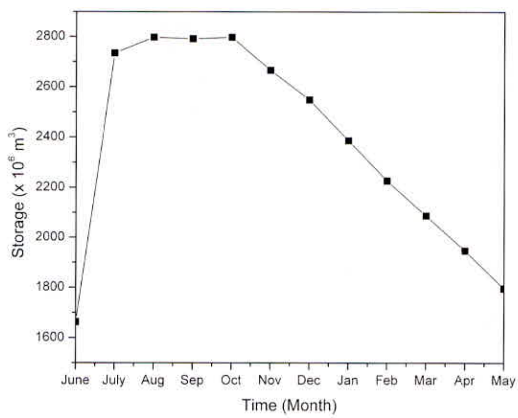

Fig. 4. Resulted final storage from the NLP model

and final storages and hence the evaporation followed a similar trend as storage. As the storage increases the evaporation is also increases and vice versa. Thus, it may be concluded that the available water can be further utilized for more hydropower generation.

CONCLUSION

Hydropower is one of the vital components of reservoir operation, especially in large multipurpose reservoirs. It is a renewable, economic, non-polluting and environmental friendly source of energy. Optimizing the reservoirs serving hydropower and irrigation are complex, since they are having conflicting objectives, if power production is not incidental. In the present study, the Koyna reservoir operation is optimized for hydropower production and irrigation using non-linear programming technique. The formulated non-linear programming model with 145 variables and 291 constraints are solved using GAMS/MINOS solver. The model resulted in an optimum power production of 2665 x 10^6 kWh. The duration of operation of powerhouses is restricted to 6 hours per day since they all are only peaking stations. The developed model has also resulted in good storage at the end of the season and the available storage can be further utilized for more hydropower generation. Thus, this study shows that Koyna dam is having more potential to generate more hydropower.

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