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DERIVING OPERATING RULES FOR MIXED PUMPED STORAGE PLANT: KADAMPARAI - A CASE STUDY

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ABSTRACT

Incorporation of storage schemes in a power system facilitates the management of peak power requirement and emergency needs. For a long period, pumped storage schemes are doing this task in efficient way. Creation and efficient use of pumped storage scheme in a critical power grid reduces the power supply uncertainties. This paper addresses the possibilities to maximize the performance by minimizing the spill of a mixed pumped storage scheme and frame expert guidance to operate the plant efficiently as suggested by Central Electricity Regulatory Commission (CERC), Government of India guidelines. A water regulation model has been developed based on hydrological mass balance with the objectives of energy maximization and spill minimization and has been applied to Kadamparai pumped storage plant, Tamil Nadu Electricity Board, India to evaluate its performance. Based on historical operation pattern, expert opinion and simulation results, monthly reservoir storage curve and operating policies have been derived with minimized spill and maximized energy output. The simulation results of the model indicate additional power production, less spill and stressed the need for a lesser storage in the lower reservoir than to maintain it very close to full reservoir level. Further, guidelines are also derived based on the simulation results and historical performance to effectively operate the pumped storage plant.

Keywords: *mixed pumped storage, simulation, water regulation model, Kadamparai pumped storage plant, operating rules. Construction and Management Aspects (CMA) and Failure and Maintenance Aspects (FMA).*

INTRODUCTION

Modern energy systems are often very complex with respect to the mix of generation sources, energy storage facilities, transmission system mechanisms, and sale of power to various customers (Bridgeman et al., 2010). The storage of reservoir represents the generation sources of the hydro energy system. Pumped storage schemes are one of the forms of large scale energy storage and are increasingly built because of their operational flexibility and ability to provide rapid response to the changes in the system loading (Kanakasabapathy and Swarup, 2008). Even though pumped storage hydro plants are operational worldwide during many decades only few numbers of pumped storage plants are commissioned in India. Scheduling of pumped storage scheme is more complex due to the inherited uncertainty in grid condition in Indian context where peak hour and energy shortage are 15% and 10% respectively as well as inflow and availability of frequency factor from the grid (Sayeed, 2005).

Kadamparai Pumped Storage scheme (KPSP) commissioned in a south Indian state is one of the present operating pumped storage schemes among the few projects commissioned in India (Velayutham and Kulkarni, 2009; Sivakumar et al., 2013). The power plants of KPSP consist of four units of 100 MW capacities and are operated from the experience gained during the past 25 years. The operation policies of the KPSP are evolved by the conditions defining the objective function of either generation or pump mode from time to time based on the aim of energy maximization according to the varying demands and as well as the spillage compulsions due to more natural inflow during rainy times. Many system models are available to arrive at the operation policies. Many general purpose Modes such as simulation models, optimization models and system analysis models based on network flow programming formulation have been developed as per the requirement of valley projects and applied to achieve higher performance of the projects (Loucks, 1992; Wurbs, 1993).

The university researchers and practitioners are very keen to apply optimization and stochastic analysis techniques related to reservoir management problems. Sule (1988) computed the reservoir water release policies for Shiroro Dam hydroelectric power scheme in Northern Nigeria using a probabilistic dynamic programming model. Simulation results of the reservoir operating policies show that the efficient use of available resources could be achieved by operating the hydropower system between 8 and 12 h per day using two or three units at a time. Lund and Guzman (1999) derived theoretical hydropower operation rules for the reservoirs in series, parallel and single reservoir. The derived hydro power rules offer a simplified economic basis for allocating storage and energy in multireservoir hydro power systems. The proposed approach was illustrated through theoretical examples. Chen et al. (2007) developed an efficient macro-evolutionary multiobjective genetic algorithm (MMGA) for optimizing the rule curves of a multipurpose reservoir system in Taiwan. MMGA gives uniformly spread solutions for a two-objective problem involving water supply and hydropower generation. The

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results show that the proposed MMGA is highly competitive and provides a viable alternative to solve multiobjective optimization problems for water resources planning and management.

Jha et al. (2008) adopted penalty factor incorporated energy maximization type objective function to reduce the spill from conventional hydro power plant of Japan. He used stochastic dynamic programming (SDP) models for obtaining the operating policy and identified storage guide curve for average year. Chang (2008) proposed a real time flood control optimization model with linguistic description of requirements and exiting regulations for rational operating decisions. Genetic algorithm was used to search the optimal releases. He used proper penalty strategy to tackle problems of greater number of constraints and flood control requirements. He applied this strategy to Shihmen reservoir in North Taiwan and found that a penalty-type genetic algorithm could effectively provide rational hydrographs to reduce flood damage. Guo et al. (2009) developed a new model based on combined guide curves for optimizing hydropower production and for better storage distribution among cascade reservoirs. They used particle swarm optimization algorithm for optimization and storage effectiveness index method for the storage allocation. The proposed model with the solution strategy is capable to produce an extra amount of electrical energy and save flood water resources annually. Zahraie and Hosseini (2009) developed a genetic algorithm (GA) optimization model for reservoir operation optimization considering variations in water demands. The uncertainties in the demands are represented by different linear equations with different combinations of inflow and storage at the beginning of the month. Classic and Fuzzy regression analysis are used to find out the coefficients of the linear equations of operation policies. They evaluated the efficiency of operation policies based on the long term operation simulation of Zayandeh-Rud reservoir in central part of Iran. The performance indices indicated that the fuzzy linear regression equations based reservoir operation had the best long term performance in meeting variable demands. Senthil kumar et al. (2012) developed reservoir operating rules using Artificial Neural Network (ANN) with Fuzzy Logic and decision tree algorithms such as M5P and REP Tree. The basic release data were utilized for developing the models using control theory. It was found that fuzzy logic model performed well compared to other soft computing techniques such as ANN, M5P and REP Tree.

It can be learnt from the application of optimization techniques carried out by many international researchers that how operating policies derived for conventional hydropower plants. But the pure optimization process is a difficult one, in the operation of pumped storage especially in Indian context, since there are large number of constraints that limit operating flexibility. Many factors affect the day to day operation of pumped storage are Supply-demand-balance of a power system, Load profiles, Generation mix and Operation policy based on its cost of generation.

Few authors have investigated the use of various inflow processes and assumptions in energy maximization and in fixing the capacity of the plant or storage requirement for a pumped storage. However, no attempt was made to explore the possibility of reducing the spill in a mixed pumped storage in its lower reservoir based on its operating conditions and based on the storage capacity of the reservoir. The sensitivity to the factors mentioned in above is of great importance in which more study programs were carried out and they mainly speaks on pricing and on optimal operation of pumped storage, etc. (Kanakasabapathy and Swarup, 2008; Geetha and Jayashankar, 2009).

This paper mainly focuses on effective reservoir regulation on real time measure as other factors associated with a mixed flow pumped storage operation in the deficient southern regional power system of India which is complex in nature and not yet analyzed so far. Further, Central Electricity Regulatory commission (CERC), Government of India, in its regulations for efficient use of pumped storage operation (CERC, 2009), insist to utilize the excess natural flow of the reservoirs which spill during the monsoon season and advised to run the plant as “must run” basis to avoid the spill and make use of the spill as utilizable energy. Hence a simulation model has been developed to derive effective operating policies for a mixed pumped storage scheme with the constraints of maximizing the energy generation by minimizing the spill.

ROLE OF PUMPED STORAGE PLANTS ON POWER GRID

Energy storage generally benefits for utilities and their customers in terms of: (i) improved power quality and reliability; (ii) reduced transmission/power losses; (iii) cost savings (e.g. deferral of new generation units and sub-station upgrades, and of new transmission lines and transformers); (iv) decreased environmental impact (lower emissions, diminished electric/magnetic field effects, integration of renewable); (v) strategic advantages (greater siting and fuel flexibility) as described in (Dell and Rand, 2001).

Pumped storage stations are the most efficient and practical technology for large scale storage of energy. By construction, these are conventional hydro power plants with the option of pumping. It consists of two reservoirs, one is located at a low level called ‘lower reservoir’ and the other at a higher elevation called ‘upper reservoir’. During off-peak hours the water is pumped from the lower to the upper reservoir where it is stored. During peak hours the water is released back to the lower reservoir, passing through hydraulic turbines generating electrical power.

Both the reservoirs may be artificial or natural based on the topology. If any natural stream flows, it may enable additional generation depending upon flood, etc. A typical pumped storage plant is shown in the Fig. 1. Pumped storage plants are designed to operate on a daily, weekly, monthly or seasonal cycle. However, most of the pumped storage stations operate on daily cycle where the storage required to support generation during morning peak and evening peak hours is replenished by pumping water using the off-peak energy available during the night/off-peak hours.

Special reversible pump-turbines are used in pumped storage stations instead of the turbines used for generation in the conventional hydro power stations, which operate as pump during pumping operation and operate as turbine in generation cycle.

mixed pumped storage plant located in the Coimbatore district of Tamil Nadu, one of the developed states of southern India and it has been planned and designed to have minimal environmental impacts. The plant has the distinction of first pumped storage plant in India operated with pumping and generation modes. It represents 10% of the total capacity of the Tamil Nadu when it was commissioned. It has been designed to store the excess energy from nuclear, thermal and hydro plants in the state and to meet the load during the peak hours.

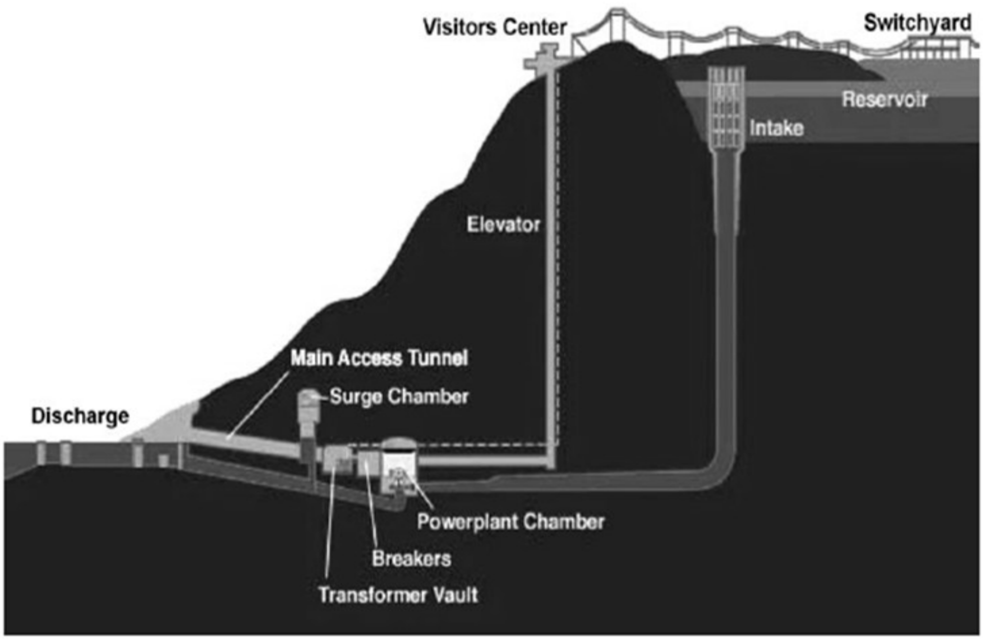

Fig. 1: Typical pumped storage plant

The pumped storage stations are planned in a power system for the following advantages: excellent load following characteristics, quick start reserves and generation capability during peak hours, leveling the peaks and valleys of the grid load curve, i.e., load leveling, stability influence right from generating to the distribution ends, reduces grid instability risks, reduces load shedding by generating energy during peak hours, allows the thermal power stations to operate at best efficiency.

Along with energy management, these systems help to control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds (Ioannis et al., 2009).

STUDY AREA

The Kadamparai pumped storage scheme of Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO), Tamil Nadu, India was commissioned in 1986 with the initial capacity of 100 MW. The plant's present capacity is 400 MW (100 MW x 4 units). It is a

The upper reservoir of the Kadamparai pumped storage plant (KPSP) is on Kadamparai river and the lower reservoir is on the Aliyar river. The Kadamparai river is the tributary of the Aliyar river. The pumped storage scheme has been developed later with the existing Upper Aliyar reservoir. The Aliyar reservoir already has two reservoirs: Upper Aliyar and Lower Aliyar reservoirs. The upper Aliyar reservoir located in Anaimalai Hills acts as the lower reservoir of the pumped storage scheme. It has a power plant of 60 MW capacity built in 1962. The lower Aliyar reservoir has also a mini hydro plant for the capacity of 2.5 MW (2 x 1.25). The tail water released from the power generating unit of the Lower Aliyar reservoir is used to irrigate the command area located downstream of the reservoir and it is under the control of PWD. The locations of these cascaded reservoirs are represented in Fig. 2.

The Kadamparai reservoir (Upper dam of PSP) located at the elevation of 1149 m has a gross storage capacity of 30.8 $\times 10^6$ m^3 and a live storage of 26.8×10^6 m^3. The height of the dam is 67.5 m, and the crest length is 808 m. The maximum flood discharge is 518 m^3/sec. The natural flow of the main stream and tributaries of the Aliyar river is diverted through the weirs such as Vandal dam, Akkamalai dam and Deviar dam through a 3558 m long diversion tunnel to create a pool for a pumped storage operation at Kadamparai Reservoir. The maximum discharge capacity of the tunnel is 42.58 m^3/sec. The diversion of the water from the weirs has increased the catchment area from 22.75 km^2 to 83 km^2. The layout of the Kadamparai pumped storage project on the Aliyar river is shown in Fig. 3.

power house is carried through tailrace tunnel of 1476 *m* long to upper Aliyar (UA) reservoir i.e., lower reservoir of PSP has an elevation of 770 *m* and live storage capacity of 21×10^3 m^3. The available head at UA is 1475 ft.

Electromechanical system:

The Kadamparai Power House is equipped with four

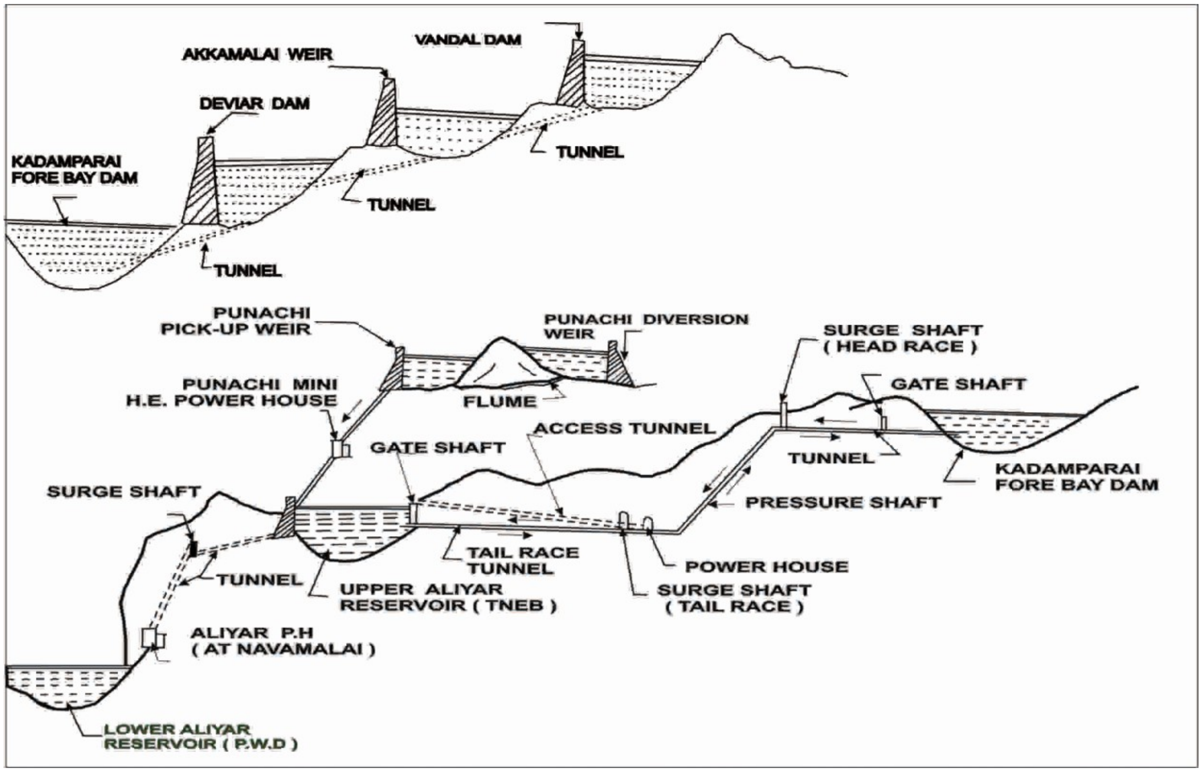

Fig. 2: Kadamparai Pumped Storage Scheme

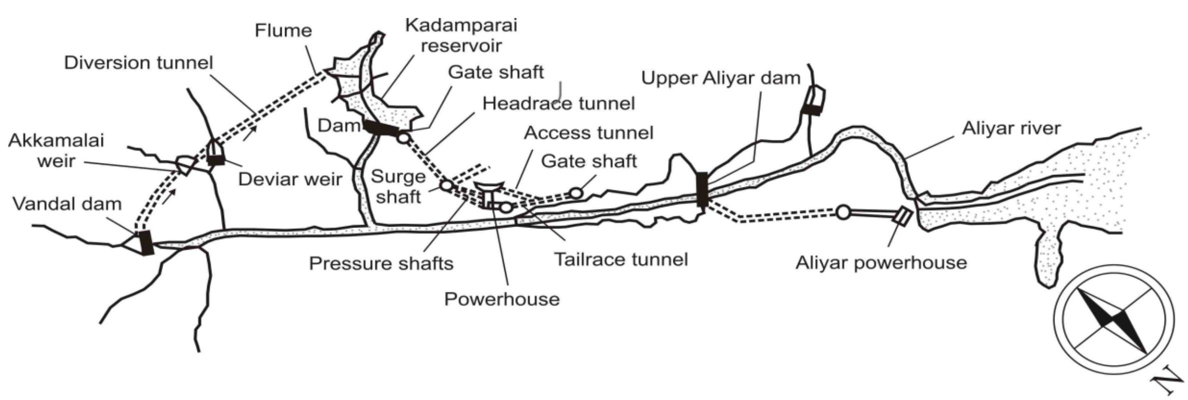

Fig. 3: Layout of the Kadamparai pumped storage project on the Aliyar river

A cavern power house located in between Kadamparai and Upper Aliyar reservoirs has four reversible pump turbine Francis units. It is 200 *m* below the ground level. The water is drawn from Kadamparai reservoir through a concrete lined headrace tunnel of 1222 m long with a discharge of 150 m^3/sec. This headrace tunnel is further divided into two pressure shafts each measuring 507 *m* long. The bifurcation of the pressure shafts forms the four penstocks to the pump turbine units. The water from the

reversible Francis turbines. The distributor centerline of each unit is at the elevation of 710 *m*. The first unit was commissioned in the year of 1987 supplied by Boving, UK. The remaining three units were supplied by BHEL, Bhopal. All the reversible units operate under the net head of 341 *m* in the turbine mode and 381m in the pump mode. The rated capacities of the machines are 102 *MW* and 107 *MW* as turbine and pump respectively (Anonymous, 1989).

OPERATIONAL PERFORMANCE OF KPH

The Kadamparai PSP has been designed to operate based on daily, weekly and seasonal scheduling. The daily load curve of TANGEDCO generally represents morning peak demand, evening peak demand and slack time at night. The operation schedule of the Kadamparai PSP always depends on the load pattern as mentioned above. During first ten years the performance of the plant was below the average level due to low grid frequency, i.e. grid was operated at less than 49 Hz. The pump at Kadamparai power house is designed to operate between 49.5 Hz and 50.5 Hz. As the grid was operated between 48 Hz and 49 Hz pump input was not available and hence poor performance. Mainly the pumping operation was carried out during weekends and national holidays, etc. Further a major fire accident occurred at the transformer cavern in the month of October 1990 and caused major outage of the station. The plant full capacity i.e. 400 MW was brought back into service in 1997 after a major renovation. Hence the plant's contribution as pumped storage was very low till the year 2000. As a turning point of Indian power industry a specialized system so called Availability Based Tariff (ABT) was introduced on 1st Jan 2003 in the Southern Regional grid i.e. grid frequency discipline was introduced between the state grids. After the introduction of ABT, KPSP operation has been brought into regional grid. This introduction of ABT has increased the plant performance considerably (around 75 % of the DPR during 2005 and 2006). The operational performance of Kadamparai plant is illustrated in Fig. 4.

records. At UA dam i.e., the lower dam of the PSP experienced spill during the monsoon months from June to December since it has only one power generating unit having the discharge capacity of 17 m^3/sec and with a small storage capacity. The volume of water utilized for the generating the power from this unit per hour is 2.16 Mcft. The combined gross capacity of both the reservoirs i.e. Kadamparai & Upper Aliyar is around 2 TMC (Thousand Mcft). But the utilizable storage limit is 1.5 TMC approximately. The remaining 0.5 TMC is the dead storage and could not be used during pumping operations. Available natural inflow from the catchment of the both reservoirs makes this PSP as a mixed PSP. Table 1 and Fig. 5 show the spill and natural inflow details of the UA reservoir from 1998 to 2010.

The total quantity of spill from 1998 to 2010 is 9528.84 Mcft. The designed generation capacity of KPSP is 797 MU annually as per DPR with the condition of 6 hrs generation and 8 hrs pumping daily, which includes 77 MU that could be generated from natural flow. Even though the KPSP is performing well among all other commissioned PSPs in the country, it has not reached the target generation as per DPR. The records of the power generation show that the maximum generation achieved by the plant was 581.45 MU in the year 2005-06. It clearly indicates the possibilities of the increasing the power generation nearer to DPR capacity by effectively reducing the spill and to do more recycling of water. The present analysis aims to minimize the spill at UA dam and convert it as utilizable energy. Whenever heavy inflow received by both the reservoirs during monsoon period effective use of the water for power generation is possible at upper dam through Kadamparai machines where as the release from Kadamparai machine plus natural inflow develops quick storage increase in the lower reservoir and because of low discharge capacity of Aliyar machine spill was noticed mainly at upper Aliyar reservoir during monsoon times.

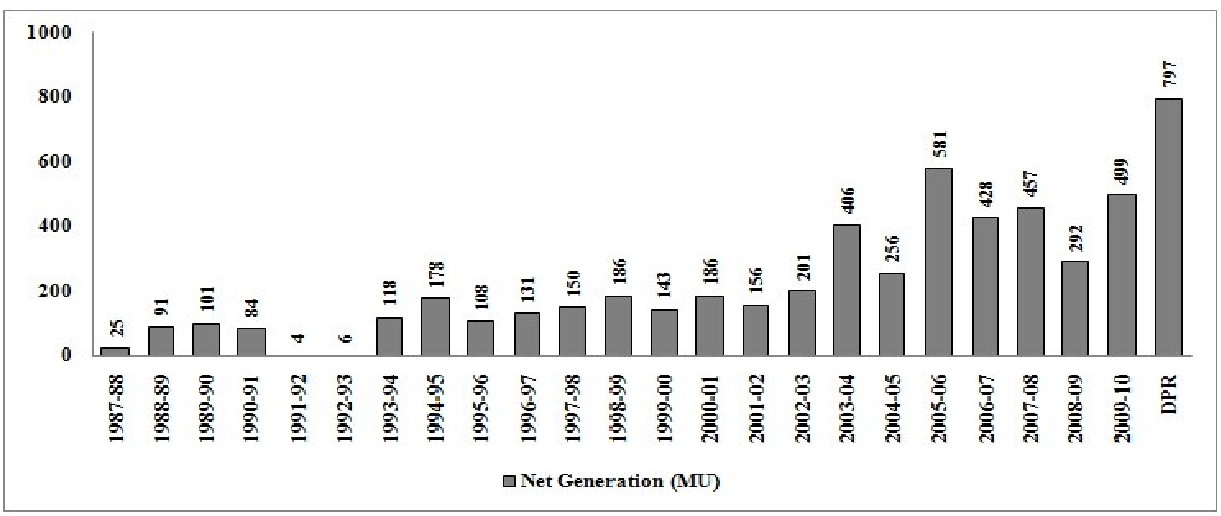

Fig. 4: Operational Performance of KPH

THE PRESENT ANALYSIS

The Kadamparai reservoir acts as upper dam of the PSP having four reversible pump turbine units. Each unit has a discharge capacity of 37.5 m^3/sec. The volume of water utilized for generating the power from all the units per hour is 16 Mcft. Because of the higher power generating capacity of the units no spill was realized for the past 10 years i.e., 2000 to 2010 at Kadamparai dam as per the TANGEDCO

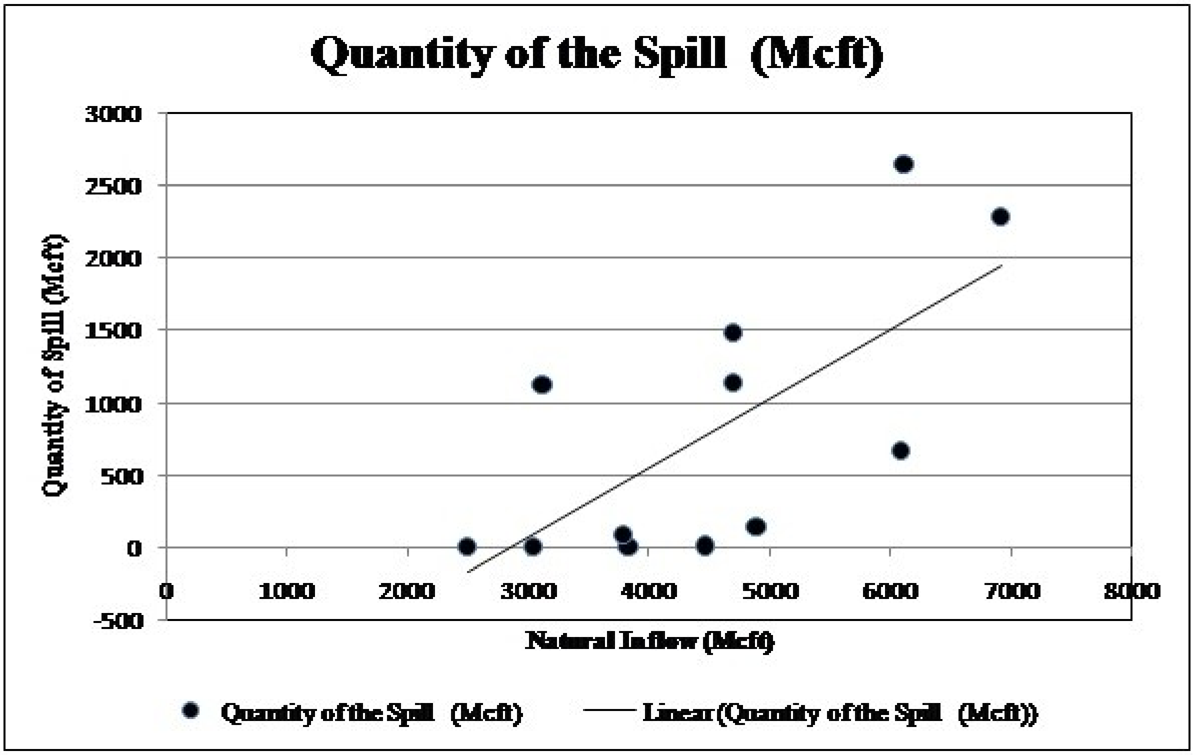

Fig. 5: Relationship of spill vs inflow

Table 1: Spill & Inflow details for the period of 1998 – 2010

Year	Natural Inflow (Mcft)	No of days spill occurred							Quantity of the Spill (Mcft)
		Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1998-99	6094	-	-	-	1	5	4	2	658.72
1999-00	4887	-	-	-	2	-	-	-	134.00
2000-01	4697	-	-	7	1	-	-	-	1129.00
2001-02	3826	No spill							0
2002-03	3039	No spill							0
2003-04	2495	No spill							0
2004-05	3114	7	9	2	-	-	-	-	1119.73
2005-06	6916	-	4	6	10	5	8	-	2284.42
2006-07	4467	-	-	-	-	1	-	-	2.52
2007-08	6114		15	13	8	7	-	-	2638.93
2008-09	3788	-	-	2	-	-	-	-	83.52
2009-10	4693	-	10	4	1	3	-	-	1478.00

In the present analysis, a water regulation model has been developed by the method of simulation to identify the power generation gap of the system. The power generation gap is filled by maximizing the discharge of the power plants. This is done by different combinations of additional discharge of both the power plants within the frame work of system. Generally, the hydropower plants are operated with a well formulated rule curves. But the operation of the pumped storage always depends on the grid conditions. The results of this analysis will also bring out certain guidelines for storage and discharge of the system to perform better with minimum spill. At the same time this study will also suggest expert ideas to operate the reservoirs based on the knowledge of natural inflow, grid conditions and historical plant operating experience.

MODEL DESCRIPTION

In general, the operation of pure pumped storage plant always depends on the grid conditions. Whereas, in the case of mixed PSPs, the operation not only depends on the grid condition, it depends on the natural flow conditions also. The KPSP is also operated for longer duration on generation mode during monsoon time since it receives sufficient amount of inflow from rainfall. The catchment of KPSP faces two seasons viz summer and winter. The winter season receives rainfall from two monsoons namely south-west (June to September) and north-east (October to December). The KPSP system receives maximum inflow during the winter season only and faces spill during this period. The inflow received during the winter season has to be stored and used to operate the plant during summer months also. The KPSP has been designed to operate daily, weekly and monthly schedules. However, the water regulation of the reservoirs has to be accounted throughout the year. Under these circumstances, the simulation of the performance of the reservoirs for few days, weeks and months will not give any suggestions for practical operation. So it has been decided to simulate the plant performance at least for few years. Based on the availability, 5 years of historical data from 2006 to 2010 have been selected for analyzing the plant performance. Keeping in view of the above, a spread sheet model has been developed to simulate the water regulation process of KPSP.

All the components of mass balance of the upper reservoir and lower reservoir have been modeled in the spread sheet. The mass balance of upper reservoir includes initial reservoir storage, natural inflow from the catchment, pump inflow from the lower reservoir, and discharge from the reservoir for power generation and spill. The mass balance of lower reservoir includes initial reservoir storage, natural inflow from the catchment, discharge for the power generation, spill from the upper reservoir, pump outflow from the lower reservoir and spill. All these components are interlinked together by the cell formulation in the worksheet. For example the entry of pump out flow from the lower reservoir is automatically passed to the upper reservoir storage. Thus the pure practical operation of KPSP has been modeled. One small hydro power plant (SHP) 'Poonachi' is also located in the KPSP hydro chain. The discharge of Poonachi SHP is naturally carried into UA reservoir. The quantity of flow and duration of operation of the plant are insignificant and the same are not considered in the development of the model. The mathematical formulation of mass balance of the reservoirs is given as follows:

Model formulation

Mass balance for reservoir 1 (Kadamparai Reservoir),

$$S1_{t+1} = S1_t + IL1_t + IP_t - Q1_t - SP1_t \quad (1)$$

Mass balance reservoir 2 (Upper Aliyar Reservoir)

$$S2_{t+1} = S2_t + IL2_t + SP1_t + Q1_t - IP_t - Q2_t - SP2_t \quad (2)$$

Where

$S1_t$ = storage of the upper reservoir at time *t*

$S1_{t+1}$ = storage of the upper reservoir at time *t+1*

$S2_t$ = storage of the lower reservoir at time *t*

$S2_{t+1}$ = storage of the lower reservoir at time *t+1*

$IL1_t$=Local inflow from the catchment of upper reservoir at time *t*

$IL2_t$=Local inflow from the catchment of lower reservoir at time *t*

$Q1_t$=Discharge from the upper reservoir for power generation at *t*

$Q2_t$=Discharge from the lower reservoir for power generation at *t*

$SP1_t$=Spill from upper reservoir at time *t*

$SP2_t$=Spill from lower reservoir at time *t*

IP_t=Pump inflow from lower reservoir at time *t*

Constraints

1. Storage constraints

$S1_{min} \leq S1_t \leq S1_{max}$ for upper reservoir (3)

Where

$S1_{min}$= minimum storage of upper reservoir i.e., 150 Mcft

$S1_{max}$= maximum storage of upper reservoir i.e., 1080 Mcft

$S2_{min} \leq S2_t \leq S2_{max}$ for lower reservoir (4)

Where

$S2_{min}$= minimum storage of lower reservoir i.e., 250 Mcft

$S2_{max}$= maximum storage of lower reservoir i.e., 980 Mcft

2. Power house generator discharge constraint for 24 hours

$Q1_t \leq 384\ mcft$ Discharge from the upper reservoir for power generation at *t* (5)

$Q2_t \leq 51.6\ mcft$ Discharge from the lower reservoir for power generation at *t* (6)

3. Pumping discharge constraint for 24 hours

$IP_t \leq 288\ mcft$ Pump inflow from lower reservoir at time *t* (7)

IP_t=Pump inflow from lower reservoir at time *t*

Simulation of the reservoirs has been done by following the mass balance equations (1) & (2) with storage, discharge and pumping discharge constraints (3) to (7) with various combinations of storage and discharge of the reservoirs to achieve minimum spill from the lower reservoir and thus to increase the power generation from the pumped storage scheme. The mass balance of the system is represented by the following Fig. 6.

SIMULATION OF THE RESERVOIRS

Normal practice adopted by TANGEDCO for operating the cascaded reservoirs is to store maximum water during rainy period and to reach FRL anticipating the monsoon failures and then utilize the inflow according to grid demand and to avoid spill of water to the extent possible. The full storage is to be used up to May of every year taking into account of other factors of grid management. The inflow from upstream reservoir is released to the downstream reservoir or for irrigation according to PWD demand for the dams under their control. Once upstream reservoir level is reached to FRL water is released either through generation or through spill discharge for irrigation. Since both

Kadamparai and upper Aliyar are TANGEDCO dams PWD is insisting water release for irrigation only during monsoon failure times. Normal operation of upper Aliyar proves its adequacy for irrigation release. However, the lower Aliyar is having a storage capacity of 4000 Mcft. It is accommodating the release from upper Aliyar through generation as well as by opening surplus gate. It could be observed from the table 1 that the spill is more during July to October at upper Aliyar dam and mainly due to monsoon inflow. Other causes of spill are meagre when compared with monsoon inflow. TANGEDCO practice emphasizes the combined storage of KPSP as 2000 Mcft at the end of monsoon period and to effectively meet the summer demand for the flexible operation almost throughout the year. The spill from UA reservoir is observed by operating the reservoirs from these existing practices. The simulation of operation of the reservoirs has been done with existing practice and the combined storage is limited to 1600 Mcft as initial condition for July to December since spill occur during this period only.

In general, increase in existing discharge from reservoirs reduces the spill and increases the generation if the condition permits. This change in discharge may reflect on combined storage of the system. The present simulation study of the reservoirs derives a new rule curve which reduces or nullifies the spill by maximizing the present discharge pattern. At the same time, the effect of the change in combined storage on the system performance has also been analyzed.

For achieving the above mentioned objectives different combinations of discharge patterns for upper and lower reservoirs have been tried. Finally two methods have been adopted in this simulation: one is 4/3 check and the other is maximizing the UA reservoir discharge only. In the 4/3 check, two numerical variables (4 and 3) have been selected for varying the discharge from upper and lower reservoirs of KPSP, i.e. adding 1 generating unit or one hour additional generation for everyday's discharge in both the reservoirs. The operation of one generation unit of KPH will replace 4mcft of water for one hour from the reservoir and UAPH generator will replace 2.15 Mcft of the water for one hour which is rounded to 3 Mcft for simulation flexibility. By analyzing the past operational data it has been observed that the maximum discharge per day from KPH was around 250 Mcft. The maximum discharge could be 384 Mcft if it is operated for 24 hours continuously. Since pumping is to be carried out regularly which will be normally between 10:00 PM and 5:00 AM, for calculation purpose, the generator operation hour is limited to 16 hours during high inflow period. It may be increased if FRL is maintained at upper dam and further inflow is continuing where there is no margin/space is available for pumping. In such occasion 24 hours generation is possible to accommodate inflow for power generation. So there is a possibility of increasing the operational duration of the plant for one hour in all the days of a month and the same is considered in the simulation analysis. The UAPH is operated to its maximum capacity in some days since it has only one generating unit. It is not possible to increase the discharge by 3 Mcft in all the days. So it is decided to increase the discharge of the plant by 3 Mcft whenever the discharge is less than or equal to 47 Mcft. During the high inflow periods, the 4/3 check method cannot be applied since it experiences the spill. In this ARE kind of situations, the second simulation has been adopted i.e., maximizing the UAPH discharge to reduce the spill to the possible extent. The above mentioned simulation methods have been carried out with existing pumping pattern of PSP. The pump is a synchronous machine, pumping is possible only when the frequency band is in between 49.5 to 50.5 Hz which always depends upon the grid. The simulation is adopted to check

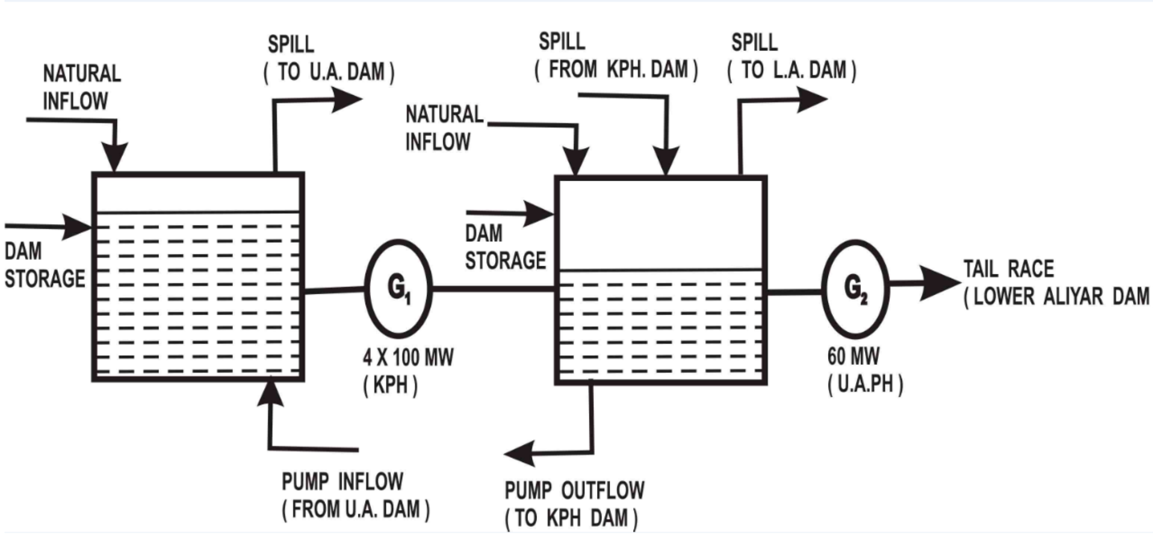

Fig. 6: Schematic diagram for mass balance of the system

the possibility of increasing the output from Kadamparai and Aliyar without increasing the pump discharge. But for pumping, we need surplus power input between 110 MW and 440 MW which could not be created for simulation purpose as a standard practice since all the southern states are facing short in generation, and demand is ever increasing and pump operation is based on day to day condition of the grid, hence changes is made in the study whenever spill is noticed in 4/3 check method.

ANALYSIS OF SIMULATION RESULTS

The two methods such as 4/3 check method and maximizing the discharge of UAPH only have been applied in the simulation analysis of the reservoirs for the years from 2006 to 2010 for the months of July to December.

Simulation results for the year 2006

TANGEDCO classifies the inflow of Kadamparai system into three categories viz. the inflow above 5000 Mcft is high inflow year, 4000 to 5000 Mcft is normal inflow year and below 4000 Mcft is low inflow year. The annual inflow to Kadamparai reservoir during 2006 was 4733 Mcft which was a normal inflow as per the classification of TANGEDCO. The power generation was 427.81 MU. The water pumped in this year was 11469 Mcft. This year was recorded as no spill year. Even though it was a no spill year, a spill of 2.54 Mcft was observed from UA reservoir on 14th October which was occurred due to the high discharge of 88.51 Mcft from upper reservoir to meet out the peak power requirement of the grid. The spill of 2.54 Mcft for this year is negligible and it is also operational spill. However simulation has been carried out for the winter season of 2006 to explore the possibilities of increase in power generation with existing operational pattern of the system. The combined storage of the reservoirs and the energy generated before and after simulation are presented in the following Tables 2 and 3.

Table 2: Combined storage pattern for the winter of 2006

Month	Before Simulation (Mcft)	After Simulation (Mcft)
Jul	1632.52	1599.52
Aug	1694.03	1574.03
Sep	1739.59	1541.99
Oct	1599.95	1321.35
Nov	1762.15	1335.37
Dec	1571.08	1109.48

An additional energy of 32.12 MU could be generated by adopting 4/3 check method in the simulation analysis. Considerable quantities of spill have been observed for the months of July, August and October. For avoiding such spills and operational flexibility of the system 155 Mcft of water has been pumped during the week ends of the above months. The regulation of the reservoirs for the next season i.e. 2007 summer has been checked after the simulation. It reveals that the combined storage reduces below 100 Mcft from 5th April onwards. Further the storage reaches below zero from 27th April and it recoups above the zero from 23 June onwards. It indicates that release pattern by 4/3 check method could not be suggested as it affects the future operation of the plant.

Table 3: Energy generation for the winter of 2006

Month	Before Simulation (MU)	After Simulation (MU)
Jul	96.65	100.66
Aug	82.21	88.62
Sep	64.68	69.84
Oct	61.89	67.24
Nov	67.65	73.15
Dec	41.42	47.10

Simulation results for the year 2007

The annual inflow during 2007 to Kadamparai reservoir was 5933 Mcft and it was a high inflow as per the classification of TANGEDCO. The power generation was 456.58 MU. The water pumped in this year was 9004 Mcft. The system experienced high spill of 2639 Mcft which was highest during the last 13 years. The operation of the KPSP was suspended from 28th May to 30th June for maintenance works. The operation of UAPH was also suspended from 6th June to 25th June for annual over haul. However the reservoir storages of Kadamparai and UA reservoir were maintained at a minimum of 246.27 Mcft and 440.82 Mcft for the future operation of the system. The monsoon was set in from 16th June onwards and gradual inflow was received till 2nd July. A notable inflow of 223.24 Mcft was observed at Kadamparai reservoir on 22nd June. Due to this vigorous monsoon the reservoir spilled 290 Mcft from 1st to 4th July. During the same period UA reservoir also received considerable inflow at regular interval. An inflow of 169.92 Mcft was observed on 13th June. For utilizing this high inflow, the Kadamparai power house was brought into operation from 2nd July onwards. The storage of UA Reservoir reached FRL due to the continuous operation of the Kadamparai power house and it caused spill. All above mentioned circumstances lead to spill of 1021Mcft and 837 Mcft during the months of July and August. The continuous monsoon and grid conditions forced the system to experience the spill of 462 and 320 Mcft during the months of September and October. The Kadamparai reservoir experienced no spill except 4 days of July due to the high unit discharge capacities whereas UA reservoir experienced continuous spill during this period since it is equipped with single power generating unit. To check adequacy of the reservoirs for regulating the inflow, operation has been simulated by maximizing the UAPH discharge method for the period of July to September. The results of the simulation are presented in Tables 4 and 5.

Table 4: Combined storage pattern for the winter of 2007

Month	Before Simulation (Mcft)	After Simulation (Mcft)
Jul	1869.86	1883.93
Aug	1987.47	1793.69
Sep	1978.06	1966.2
Oct	1733.04	1626.45
Nov	1426.51	1347.69
Dec	1715.35	1476.9

Table 5: Energy generation for the winter of 2007

Month	Before Simulation (MU)	After Simulation (MU)
Jul	87.02	99.87
Aug	75.27	91.31
Sep	79.92	88.77
Oct	77.63	98.41
Nov	77.32	82.40
Dec	49.25	55.78

The mass balance of the model for this year has been done by taking the data of 2010 from 28th May to 30th June for Kadamparai reservoir and from 6th June to 25th June for UA reservoir since the operation of the plants was suspended during these periods. The imposing of the data of 2010 induces spill (approximately 800 Mcft) from UA reservoir. However the simulation by maximizing the UAPH discharge method reduces these spills considerably. Further same simulation method has been adopted for the months of August, September and October also. No spill is observed for the months of September and October. A considerable amount of spill is reduced during the month of August. The simulation of reservoir operation for months of November and December has been done by 4/3 check method. The results of the simulation for December reveal that a negligible amount of spill is observed and it could be avoidable by practical operation. An additional energy of 70.14 MU has gained from the simulation analysis.

The simulation of the year 2007 divulges the following observations:

- Uncertainty in predicting the monsoon increases the difficulty of reservoir regulation. However during monsoon period according to the inflow, maximum discharge of UA Reservoir is to be utilized and effective pumping and generation has to be used to balance the reservoir regulation.
- When both the reservoirs reach their maximum even after full discharge of UA, spill occurs. It is natural and beyond control of the reservoir regulation.
- In high monsoon period, operation on allowing less combined storage is recommended since spill would occur if the inflow is high and continuous.
- Once both the reservoirs reach their FRL, the only possible discharge is through UAPH which imposes the restriction of 51.6 Mcft/day. Hence it is recommended to operate UAPH at the maximum and keep the combined storage to the extent possible for flexible generation and pumping operation of KPSP, for which again it is recommended to keep the combined storage at lesser level.

Simulation results for the year 2008

The annual inflow during 2008 to Kadamparai reservoir was 4018 Mcft and it was a normal inflow as per the classification of TANGEDCO. The power generation was 291.72 MU. The water pumped in this year was 7613 Mcft. The system experienced spill only on two days which amounts to 84 Mcft. Even though the spill is of negligible quantity the simulation has been carried out to check the possibility in improving the performance of the plant. The combined storage for the month of July 2008 is about 727 Mcft. The storage of Kadamparai reservoir is 242 Mcft. The simulations with 4/3 check method leads to the reservoir level below MDDL. So, it will not be a practical solution. Hence the simulation has not been carried for this month. The simulation results for the remaining 5 months August to December 2008 are given in Tables 6 and 7.

Table 6: Combined storage pattern for the winter of 2008

Month	Before Simulation (Mcft)	After Simulation (Mcft)
Jul	24.67	24.67
Aug	65.79	71.01
Sep	36.42	41.92
Oct	30.03	35.28
Nov	37.56	43.06
Dec	42.66	48.15

The 4/3 check method reduced the spill considerably. Only few operational spills have been observed for the months of August, November and December which can be eliminated by practical operation. As per simulation, an amount of 26.96 MU is gained as an additional energy.

Table 7: Energy generation for the winter of 2008

Month	Before Simulation (MU)	After Simulation (MU)
Jul	1469.72	1377.90
Aug	1458.62	1345.55
Sep	1735.03	1531.96
Oct	1899.51	1615.44
Nov	1842.25	1461.60
Dec	1899.00	1380.88

Simulation results for the year 2009

The annual inflow during 2009 to Kadamparai reservoir was 4828 Mcft and it was a normal inflow as per the classification of TANGEDCO. The power generation was 98.81 MU. The water pumped in this year was 15080 Mcft. The system experienced spill of 1478 Mcft. The spill in July, August, September and October were 894, 163, 32 and 389 Mcft respectively. The spill in the month of July was due to grid demand and monsoon condition. The spills in other months were due to grid demand only. Under this circumstances, the simulation has been done with only maximizing the UAPH discharge for the months of July, August, September and October since system experienced more spill. The simulation for the remaining two months November and December have been carried by 4/3 check method. The simulation results for the year 2009 are given in Tables 8 and 9.

In the month of July, though the combined storage is maintained at 904.77 Mcft, the storage level has been found gradually raised even after allowing maximum discharge of UAPH and a spill has occurred from 19th July since the increased monsoon inflow from 13th July to 20th July made the water level in both the reservoirs to reach the FRL. However, the reservoir storage has been brought back to 850 Mcft (Combined storage) by running the power plants. A possible reduction of spill can be achieved by reducing the combined storage by releasing more water during the month of June through UAPH. The simulation with more release during June indicates that the combined storage has been reduced to 815.92Mcft and the spill from 894 Mcft to 323.28 Mcft. The spill for months of August and September has been nullified by operating UAPH to the maximum extent and regulating the pumping and generation of the system. The spill has been observed in the month of October after the simulation but it may be avoided by practical operation of the power plants. But the months of November and December 4/3 simulation method has been adopted and found no spill.

Table 8: Combined storage pattern for the winter of 2009

Month	Before Simulation (Mcft)	After Simulation (Mcft)
Jul	1866.35	1940.77
Aug	1630.96	1617.96
Sep	1547.39	1549.43
Oct	1021.89	1334.72
Nov	1512.94	1427.05
Dec	1531.98	1362.09

Simulation results for the year 2010

The annual inflow during 2010 to Kadamparai reservoir was 3740 Mcft and it was a poor inflow as per the classification of TANGEDCO. The power generation was 572 MU. The water pumped in this year was 13447 Mcft. The system experienced no spill in this year. However, the simulation has been done to check the possibility of gaining power generation. The 4/3 simulation method has been adopted for all the months of winter season. The simulation results for the year 2010 are given in Tables 10 and 11.

Table 9: Energy generation for the winter of 2009

Month	Before Simulation (MU)	After Simulation (MU)
Jul	83.43	100.87
Aug	56.75	64.32
Sep	77.25	78.50
Oct	85.05	89.16
Nov	71.64	75.64
Dec	59.88	65.32

Table 10: Combined storage pattern for the winter of 2010

Month	Before Simulation (Mcft)	After Simulation (Mcft)
Jul	1801.74	1725.85
Aug	1805.04	1646.88
Sep	1799.29	1513.07
Oct	1756.28	1356.95
Nov	1888.7	1389.72
Dec	1713.31	1118.93

Table 11: Energy generation for the winter of 2010

Month	Before Simulation (MU)	After Simulation (MU)
Jul	65.54	70.96
Aug	64.15	68.75
Sep	53.18	58.68
Oct	60.81	66.33
Nov	71.05	76.38
Dec	84.27	89.78

The simulation results indicate that no spill has been found in the month of July. During the month of August, UAPH has utilized its maximum capacity to meet the higher grid demand (Load shedding imposed from the year 2008 in the state). In this context, adding 3 Mcft with UA discharge is possible for only few days. So the simulation for this month results spill for only three days. These spills may not occur in practical operation. Similarly the remaining months of the winter season also indicate 2 to 3 days spill in every month for the above reason.

SUMMARY OF THE SIMULATION

The analysis of Inflow from year 1998 to 2010 clearly indicates that KPSP experienced normal inflow in most of the years as per TANGEDCO classification. The inflow is more during the month of July in comparison to the other months. Table 12 accounts the number of days in a month when the inflow is more than 50 Mcft and also mentions whether the particular month experienced spill or not. Whenever heavy monsoon set-in, the inflow was accommodated to the maximum storage capacity of both the reservoirs and rest of the inflow was allowed as spill. The maximum one day inflow during this period was approximately 200 Mcft. These conditions would facilitate for framing the reservoir operating rules.

Table 12: Spill of the days above 50Mcft inflow

Year	Month	No. of Days above 50 Mcft inflow	Spill
2006	June	5	NS
	July	7	NS
	August	4	NS
2007	June	5	NS
	July	12	S
	August	7	S
	September	6	S
	October	4	S
	December	2	NS
2008	July	7	NS
	August	4	S
	September	4	NS
	October	1	NS
	November	1	NS
2009	June	1	NS
	July	15	S
	September	4	S
	October	4	S
	November	2	NS
2010	June	2	NS
	July	7	NS

NS - No Spill ; S – Spill

The different scenarios of combined storage are given in the Figure 7. The average combined storage is the average of 10 years combined storage of Kadamparai and UA reservoirs. The simulated combined storage is the average of five years simulated results from 2006. The plot for the year 2007-08 reveals the maximum level maintained at the reservoirs during the months of July, August and September.

By analysing the graphs, it is understood that the average combined storage curve is better than simulated combined storage curve. But the curve derived from the simulation has minimized or nullified spill. At the same time a point should be kept in mind that the simulation for the year 2006 would affect the next year operation. Similarly the simulation of the year 2010 may also affect the next year operation. Since the reservoir utilised maximum possible limits and also it was poor inflow year. As per the storage is concerned, the year 2010-11 can be considered as ideal storage year for running the plant in a most efficient way. Further, the state experienced severe power shortage in this period and hence the KPSP utilised to the maximum extent possible to meet out the critical needs of the grid. Even this year was a poor inflow year, the reservoirs were utilised to the maximum extent for the above reason. So for future operation, the 2010-11 storage pattern with effective pumping and generation can give better performance of the system. The maximum, minimum and average storage limits from simulation and past 10 years actual operation are listed in Tables 13, 14 and 15.

The combined storage is the most important parameter for pumped storage operation. The above results help to fix the combined storage with maximum system performance and minimum spill. However suggestion for the operation of the individual reservoir is also important to improve the overall performance of the system effectively with minimum spill. The following guidelines are derived from simulation results and historical performance of the system.

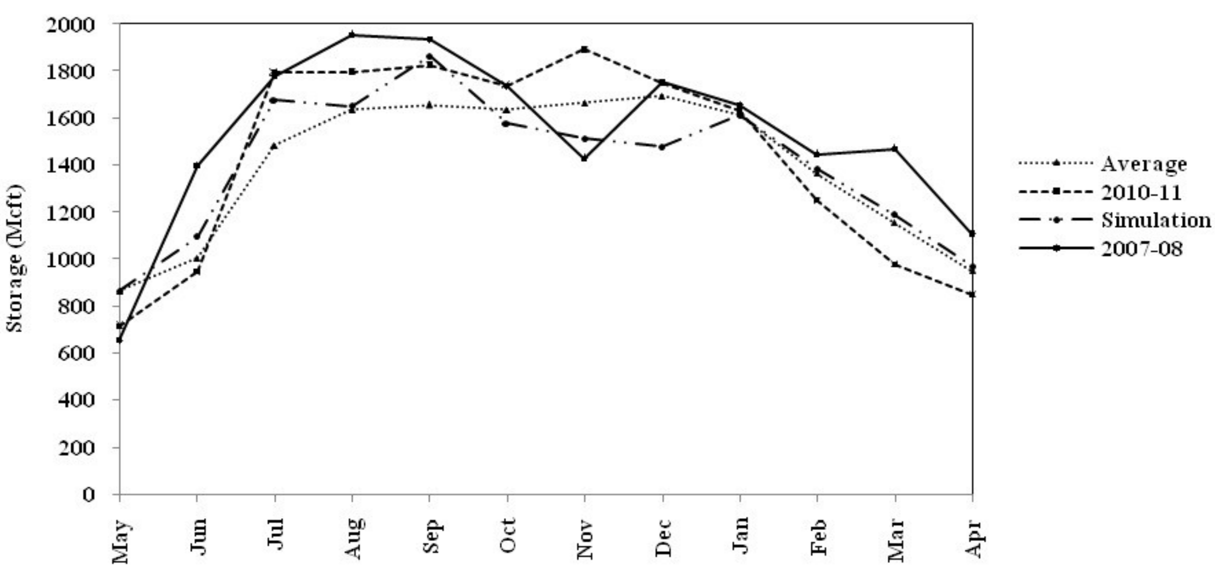

Fig. 7: Plot of Combined storage for 10 years Average, Simulation, 2010-11, 2007-08

Table 13: Combined storage level from simulation

	July	August	September	October	November	December
Average	1676	1650	1865	1578	1514	1480
Max	1855	1918	1966	1916	1948	1949
Min	1471	1322	1550	1336	1356	1155

Table 14: Combined storage level from 10 years historical pattern

	July	August	September	October	November	December
Average	1484	1635	1655	1636	1666	1695
Max	1871	1954	1912	1923	1921	1906
Min	424	1284	1292	1025	1381	1284

Table 15: Combined storage level from 10 years historical pattern

	January	February	March	April	May	June
Average	1616	1364	1155	950	866	1006
Max	1914	1663	1468	1234	1453	1515
Min	1182	845	821	675	409	556

- Keep UA dam level below 30% of its gross storage up to November 15th
- From July to November the combined storage should not exceed 1800 Mcft (since maximum one day natural inflow recorded is approximately 200 Mcft during past 5 years).
- The capacity of UA dam should not be increased above 800 Mcft at winter season.
- Operate UAPH to the maximum extent possible during winter period especially if the inflow is continuous, so that storage is limited below 800 Mcft.

reservoir than to maintain it very close to full reservoir level.

Being equal capacity of upper and lower reservoir, gradual increase of storage in the lower reservoir is causing concern in its optimal operation during monsoon season and also during must run condition. Must run condition is to be satisfied while maintaining a lesser storage in the lower reservoir besides power station scheduled operations [Refer table 16].

Table 16: Possible hours of generation in critical condition

Sl. No	KP Dam Storage	UA Dam Storage	Combined Storage	UAPH Discharge	Storage / Discharge	Hours
1	950	250	1200	Nil	700/16	44
2	850	350	1200	Nil	500/16	31
3	750	450	1200	Nil	300/16	19
4	650	550	1200	Nil	100/16	6

- It is recommended that if the monsoon is heavy and continuous, keeping the lower reservoir storage at an optimum capacity between 700Mcft to 800 Mcft with a combined storage of 1600 Mcft.

CONCLUSIONS

A simulation model to check and reduce spill noticed in a pumped storage plant has been developed and implemented in this research work. Results obtained from the application of the model indicate possibility of the improvement over the existing operating policies. Operating rules have been framed based on existing operating condition and compared with the simulation results. The developed model has been tested by changing reservoir outflows during monsoon season. Results indicate additional power production, less spill and stressed the need for a lesser storage in the lower

Assumptions:

- No inflow on both the reservoirs and Kadamparai power house is operated to its full capacity
- Combined storage kept at 1200 Mcft for example.

Based on the historical rainfall data, considering the use of the station as a pumped storage at the present regional grid conditions, its need towards summer demand and anticipating uncertainty on the climate condition, it is recommended to maintain the storage as 800 Mcft or lesser in the lower reservoir during monsoon.

FUTURE RESEARCH

Further research on reservoir regulation has to be continued so as to obtain an optimal storage level and the discharge pattern from the lower reservoir based on inflow and also anticipating its future increased operation on its move towards designed projection of power generation and considering the future inclusion of the thermal, nuclear and wind parks in the state.

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