Optimizing Energy Output at Canyon Hydro Power Station, a Case Study

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Abstract— *Due to the rain fed central hills in Sri Lanka, the country enjoyed low cost, renewable hydro electricity generation since 1950's. With the completion of nearly all major hydro site developments and the growth in electricity demand hydro generation currently contributes only 40% to the gross electricity generation in the country. In view of increasing dependence on carbon polluting fuels for electricity generation, development and utilization of hydro power potential to the maximum level and in an optimum manner would bring multiple benefits.*

This paper presents a case study to achieve optimum generation at the Canyon, new Laxapana cascade. Current practice of loading cascaded Laxapana complex plants is mainly based on meeting pond balancing constraints and the spinning reserve requirements. Efficient performance of the plants are not given due consideration in the dispatch process. However, such considerations would lead to loading patterns which generate same amount of electricity using less water due to the fact that especially in case of Francis turbiness the efficiency significantly varies with the load. As an example a single Canyon unit delivering 14.56 MW at full reservoir level uses 0.578 m3 of water per second per MW whereas the same unit delivering 25.57 MW needs only 0.553 m3/s per MW. Further, when both machines are running in parallel the resulting head loss is higher than that when a single machine operates to give the same output. An algorithm is developed to obtain all the requested energy output within a specific period using minimum of water. Rescheduling the dispatch of plants by the new algorithm saved 64388 m^3 *of water while generating 722MWh of energy. The water saved could generate 29.5 MWh on a later date and amounting to a saving of 4.1% in energy terms. As similar savings can be achieved almost every day implementation of this algorithm would lead to avoidance of cost through reductions in thermal generation and associated GHG emissions.*

Keywords: *Cascaded hydro power plants*, *efficient operation*

I. INTRODUCTION

With the continuous growth of Sri Lankan GDP backed by the growth of economy, population and the growth in access to goods and services that use electricity in their life cycle, import of fossil fuels for generation of electricity has increased over the past three decades. In the four years from 2010 to 2013, 65% of the .. GWh generated were from thermal power plants burning imported fuel. In view of this it is becoming increasingly important to shift the fuel diversity towards more and more indigenous primary energy sources for electricity generation. Further, it is equally important to utilize existing capacity based on renewable resources in an optimum manner. The savings on GHG emissions would be a bonus resulting from such efforts. This paper investigates ways to generate more electrical energy using the same amount of water at power stations that are already in operation taking Canyon power plant for he case study.

II. POTENTIAL FOR HYDRO POWER GENERATION IN SRI LANKA

Sri Lanka is blessed with many sites ideal for hydro power generation and the development of most of such sites with potential capacity of over 10 MW have been completed by 2012. Master plan for the electricity supply of Sri Lanka, completed in 1989, can be considered as the most comprehensive study carried out so far on the assessment of the large hydro electric potential of Sri Lanka [1]. Considering all the sites capable of generating over 10 MW, the total potential yet to be developed amounts to be 630 MW with an expected annual energy output of 2,513 GWh [1]. Out of these sites construction work has already started or planned at Broadlands, Uma Oya, Moragolla and Gin Ganga. These four projects would add around 250 MW of total capacity and an expected annual energy of 904 GWh.

Sites with potential capacity not exceeding 10 MW are classified as small hydro in Sri Lanka. Development of such sites can be undertaken by private sector facilitated by the Standard Power Purchase Agreement (SPPA) through which Transmission licensee becomes the guaranteed buyer. This arrangement has led to fast development of small hydro sector in Sri Lanka and the total installed capacity stood at 267 MW from 131 power plants at the end of 2013. The total generation from such plants amounted to 565 and 916 GWh in years 2012 and 2013 respectively [2]. It should be noted that the year 2013 was an excessively wet year. In addition to the Master Plan Study carried out in 1989 [1], a comprehensive, though not exhaustive, study on exploitable hydro potential in Sri Lanka was carried out by Intermediate Technology Development group (ITDG)in 1999 [3]. However, the estimated potential as exploitable small hydro in both these studies have now been exceeded. This is partially due to the fact that developments afterwards have made many sites feasible that were ignored or considered infeasible in the studies. Based on the Letter Of Intent (LOI) lodged, there have been 341 MW undeveloped potential at the end of 2010. Considering 175 MW capacity that were in operation by that time total potential would exceed 500 MW.

As the number of sites as well as the amount of water in reservoirs/ponds is limited best exploitation of such resources bring multiple advantages. The salient benefits are the savings on foreign exchange spent on primary energy imports and reduction of GHG emissions. If the amount of water used per kWh can be reduced by better dispatch schedules the existing power can generate more energy without requiring additional capital investments. Thus, optimized dispatch schedules, optimized pond balancing [4] and more strenuous catchment management can add more clean and indigenous energy into our system.

A. Optimizing the water requirement to generate a unit of energy

A power plant in operation produces three products in parallel; they are energy measured in kWh, reactive power measured in kVar and the spinning reserve capacity estimated in MW. Each of these three products has a monitory value. In this analysis, we assume that the power factor is kept constant and thus the KVar production is not a parameter. Then the main output is the amount of energy (kWh) generated. The amount of water used for generation of a unit of energy depends on the reservoir water level, overall head loss and the plant efficiency. The reservoir water level decides the gross head that is available and is an independent parameter. If the power factor is kept constant the plant efficiency is a function of the operating point i.e. the amount of guide vane opening. In a single turbine operation the head loss is a function of the discharge again decided by reservoir water level and guide vane opening. However, most of the power stations have two or more turbines working in parallel and water used by such turbines share the same tunnel and sometimes the same penstoke inlet. In such situations the head loss is jointly decided by quantities of water used by each of the turbines.

In case of the Canyon power station taken for this case study, water fist enters a larger tube and then branches out into two parallel penstokes. In this arrangement the head loss is very much dependant on whether one unit is running or both units are running in parallel.

Canyon power plants are permitted to operate at reservoir levels between 1,167.38 m and 1,145.44 m. Tail race elevation varies between 963.17 (flood situation) and 958.00 (fixed level of the weir).Thus the net head can theoretically vary between 182.27 and 209.38.

As our objective is to find out the operating point at which the minimum amount of water is taken to generate a unit of energy, the discharge in m^3/s per MW of real power at constant power factor (here taken as 0.85 lagging) is considered. At the maximum permitted reservoir level of 1,167.38 the best operating point is at 70.3 mm guide vane opening which gives a discharge of 14.13 m^3/s and a generator output of 25.570 MW and corresponds to a discharge of 0.553 m^3/s per MW. Francis turbine efficiencies vary over a significant range for different guide vane opening levels. At the above reservoir level when guide vanes are 30.1 mm opened, which is the smallest possible opening, the minimum turbine efficiency prevails. In this level of opening the discharge and the generator output amount to 6.27 m^3/s and 10.081 MW respectively corresponding to a discharge of 0.622 m^3/s per MW The highest possible level of guide vane opening is 100.5 mm and this corresponds to discharge and generator outputs of 18.56 m^3/s and 32.138 MW respectively leading to a specific discharge of 0.578 m^3/s per MW. This information corresponding to three reservoir levels is tabulated in table 1 below:

Table 1: Water requirement per generated MW at different guide vane openings, single unit operation

Reservoir level (m)	Guide vane opening (mm)	Discharge (m^3/s)	Generator output (MW)	Specific discharge (m^3/s per MW)
1,167.38	100.5	17.51	27.936	0.627
	60.3	11.92	20.585	0.579
	30.1	6.23	9.854	0.632
1,164.34	100.5	17.33	27.228	0.636
	60.3	11.80	20.117	0.587
	30.1	6.16	9.555	0.645
1,145.44	100.5	16.16	23.063	0.701
	60.3	10.99	16.905	0.650
	30.1	5.72	7.931	0.721

From Table 1 we can see that the best operating point is at 70.3 mm opening of the guide vanes and the specific water requirement varies from 0.553 to 0.713 m^3/s per MW. It is also seen that lot of water (up to 15%) can be saved if the operating point is maintained at a point close to the optimum. If the Canyon power station is to deliver 20 MWh during the day time, considering the energy requirement only, the best solution is to run a plant at 70.3 guide vane opening level for 0.957 hours which would consume 44,707 m^3 of water. The worst solution is to run the same plant for 2.479 hours at 30.1 mm guide vane opening which would consume 51,314 m^3 of water. Thus, in the second solution 14.7% more water is consumed to generate the same quantity of energy. The optimum solution will be more complicated if the other constraints such as power requirement and spinning reserve requirement are taken into account.

The situation changes if both plants are running equally loaded. Here the amount of water passing through the common parts of the water way approximately doubles and give rise to increased head loss for each of the plants. As a result, the specific water requirement increases and the values are given in table 2 below:

Canyon power station is a special case where parallel operation of both units increases the head loss significantly. From the values in table 2 it is observed that the discharge corresponding to the best operating point changes from 0,555 to 0,579 m^3/s per MW. This is an increase of 4.3% in water usage to generate the same amount of energy. It is also seen that the best operating point shifts from 70.3 mm opening to 60.3 mm opening.

Table 2: Water requirement per generated MW at different guide vane openings, two unit operation

Reservoir level (m)	Guide vane opening (mm)	Discharge (m^3/s)	Generator output (MW)	Specific discharge (m^3/s per MW)
1,167.38	100.5	18,56	31.138	0.578
	70.3	14.13	25.570	0.553
	30.1	6.27	10.081	0.622
1,164.34	100.5	18.37	31.345	0.586
	70.3	13.99	24.925	0.561
	30.1	6.22	9.791	0.635
1,145.44	100.5	17.15	26.596	0.645
	70.3	12.98	20.904	0.621
	30.1	5.75	8.068	0.713

However, Canyon power station can't be operated in isolation as it is in cascade with New Laxapana power station and the water output rom new Laxapana flows to Laxapana pond along with the output for old Laxapana power plants. Laxapana pond feeds the Samanala power station. Thus any optimization is to be done in such a way that no pond is subject to spilling and there is no shortage of water for the downstream plants that are in cascade.

Considering the above constraints and given the energy requirement and the spinning reserve requirement it is possible to find out the best operating schedule that uses the minimum amount of water. Mathematical formulation of this optimization problem is discussed in section IV.

III. MINIMIZING THE WTER REQUIREMENT FOR A REQUESTED QUANTITY OF GENERATION IN THE CANYON, NEW LAAPANA AND SAMANALA CASCADE

Following assumptions are made in order to simplify the problem:

1. The total power and energy outputs from the whole Laxapana complex is at a known fixed value for the duration of the time interval T.
2. The outflow from Old Laxapana is fixed at a given value.
3. Inflows to the Canyon and Laxapana ponds are constant at a known value during the time interval and are relatively small compared to the outflows from the plants.

There is some interdependency of this problem on the water output from Wimalaurendra, Old Laxapana cascade as both waters flow into the same pond supplying Samanala power station. With the assumption 2 above this dependency is switched off reducing the number of variables associated with the problem.

The following notations are introduced:

P_{Total}: Total power requirement during the interval T
P_{OL}: Total power output from Wimalasurendra,and Old Laxapana plants
P_{Can1}: Power output from Canyon unit 1
P_{Can2}: Power output from Canyon unit 2
P_{NL1}: Power output from Old Laxapana unit 1
P_{NL2}: Power output from Old Laxapana unit 2
P_{Sam1}: Power output from Samanala unit 1
P_{Sam2}: Power output from Samanala unit 2
Q_{OL}: Total discharge from Old Laxapana plants
$Q_{Can}(P_{Can1}, P_{Can2})$: Total discharge from Canyon plants
$Q_{NL}(P_{NL1}, P_{NL2})$: Total discharge from New Laxapana plants
$Q_{Sam}(P_{Sam1}, P_{sam2})$: Total discharge from Samanala plants
Q_{ICan}: Inflow rate to Canyon pond
Q_{ILax}: Inflow rate to Laxapana pond

It should be noted that the functions $Q_{Can}(P_{can1}, P_{Can2})$, $Q_{NL}(P_{NL1}, P_{NL2})$ and $Q_{Sam}(P_{Sam1}, P_{Sam2})$ are non-linear functions that also depend on the respective reservoir/pond levels. The function behaviors are known in tabular form. The optimization problem can now be formulated in the following manner:

$Q_{can}(P_{can1}, P_{can2})$ is to be minimized in such a way that

$$P_{total} = P_{OL} + P_{Can1} + P_{Can2} + P_{NL1} + P_{NL2} + P_{Sam1} + P_{Sam2}$$

$$Q_{NL}(P_{NL1}, P_{NL2}) = Q_{Can}(P_{Can1}, P_{Can2}) + Q_{ICan} \pm \Delta Q$$

$$Q_{Sam}(P_{Sam1}, P_{Sam2}) = Q_{OL} + Q_{NL}(P_{NL1}, P_{NL2}) + Q_{ILax} \pm \Delta Q$$

The ponds have some storage capacity and thus in- and outflows to them need not be equal all the time. In some situations it is required to fill or empty the ponds in order to get ready for next time duration. To facilitate this a ΔQ variation is introduced to the discharge balance equations.

As this is a non-linear optimization problem, combinatorial solution methods can be used. The cost function is evaluated for all the feasible combinations and the optimum is obtained. Before accepting the solution cross checks for the pond spilling will be done. In critical cases other constraints like the spinning reserve requirements can also be cross checked. If the optimum solution does not satisfy any of these conditions the next best solution is accepted. Power values are varied in reasonably small steps to reach the optimum.

In order to evaluate the saving potential through this approach a selected one-day dispatch schedule is optimized. Non-optimized schedule is the schedule given by the System Control Center without considering the water usage in Canyon turbines. The optimized schedule is the one obtained through the optimization methodology described above. The comparison of results and resulting saving on water is given in Table 3 below:

Table 3: Optimized dispatch schedule for a selected day

Time interval	Dispatch schedule $P_{OL}+P_{Can1}+P_{Can2}+P_{NL1}+P_{NL2}+P_{Sam1}+P_{Sam2}$	
	System Control version	Optimzed version
0.00-1.00	58.5+15+0+45+45+36.9+37.7=238.1	58.5+25+0+42+42+35.4+35.2=238.1
1.00-2.00	58.5+15+0+45+45+37.3+37.4=238.2	58.5+25+0+41+42+35.8+35.9=238.2
2.00-3.00	58.5+15+0+45+45+37.1+37.6=238.2	58.5+25+0+41+42+35.6+36.1=238.2
3.00-4.00	58.5+15+0+50+50+37.2+37.5=248.2	58.5+25+0+47+47+35.2+35.5=248.2
4.00-5.00	73.5+25+24+50+50 + 37+37.5=297	73.5+25+24+50+50+37+37.5=297
5.00-6.00	73.5+25+24+50+50 + 37.3+37.8=297.6	73.5+25+24+50+50+37.3+37.8=297.6
6.00-7.00	68.5+15+15+40+40 + 37.4+37.7=253.6	68.5+25+24+43+43+37.4+37.7=253.6
7.00-	46+10+10+30+30+	46+0+24+28+29+

8.00	32.1+32.5=190.6	32.1+31.5=190.6
8.00-9.00	46+10+10+50+50+36.9+37.5=240.4	46+0+23+49+49+36.9+36.5=240.4
9.00-10.00	46+10+10+50+50+32+32.4=230.4	46+0+23+49+49+32+31.4=230.4
10.00-11.00	46+10+10+50+50+32.2+32.4=230.6	46+0+23+49+49+31.2+32.4=230.6
11.00-12.00	46+20+20+50+50+37.5+32=255.5	46+0+25+50+50+37.5+37=255.5
12.00-13.00	46+15+15+50+50+37.7+32=245.7	46+0+25+50+50+37.7+37=245.7
13.00-14.00	56+15+15+45+45+37.5+37.4=250.9	56+0+24+48+48+37.5+37.4=250.9
14.00-15.00	56+15+15+50+50+37.4+37.5=260.9	56+0+30+50+50+37.4+37.5=260.9
15.00-16.00	56+15+15+50+50+36.8+37.5=260.3	56+0+30+50+50+36.8+37.5=260.3
16.00-17.00	51+15+15+50+50+32.2+32.3=245.5	51+0+24+49+49+36.2+36.3=245.5
17.00-18.00	68.5+10+10+50+50 + 37.2+37.6=263.3	68.5+0+24+49+49+36.2+36.6=263.3
18.00-18.30	68.5+10+10+50+50 + 37.7+37.5=263.7	68.5+0+24+49+49+36.7+36.5=263.7
18.30-19.00	98.5+25+24+45+45 + 37.6+37.6=263.7	98.5+20+20+50+50+37.6+36.6=263.7
19.00-19.30	98.5+25+24+50+50 + 37.3+37.6=322.4	98.5+25+24+50+50+37.3+37.6=322.4
19.30-20.00	98.5+25+24+50+50 + 37.6+37.7=322.8	98.5+25+24+50+50+37.6+37.7=322.8
20.00-20.30	98.5+25+24+50+50 + 37.6+37.5=322	98.5+25+24+50+50+37.6+37.5=322
20.30-21.00	98.5+25+24+50+50 + 37.7+37.6=322.8	98.5+25+24+50+50+37.7+37.6=322.8
21.00-22.00	78.5+25+24+40+40 + 37+37.5=282	78.5+20+20+44+45+37+37.5=282
22.00-23.00	78.5+25+24+45+45 + 37.3+37.5=292.3	78.5+20+20+49+50+37.3+37.5=292.3
23.00-24.00	68.5+0+15+45+45+37+37.5=248	68.5+0+15+45+45+37+37.5=248

Both of the dispatch schedules give same amount of energy to the system. As the generation from Wimalasurendra- Old Laxapana cascade is kept unchanged, same quantity of water is drawn from the Castlereigh reservoir in implementation of both of the schedules. The optimized schedule effective only if there is a saving in water drawn from Moussakelle reservoir. The total amount of water drawn for the original schedule is 1,564,313 m^3. If the optimized schedule is implemented this amount reduces to 1,499,925 m^3leading to a saving of 64,388 m^3 (4.1%) for the day. Water saved this way can be used to generate electricity from all the power plants in the cascade and thus have a very high energy value. Further, such water can be stored in the reservoir for longer periods and could be used for generation during more critical time periods.

IV. CONCLUSION

With ever increasing costs of primary energy imports for electricity generation, we have to better manage our indigenous resources like water used for hydro power generation. The fact that the efficiency of Francis type turbines vary over a wide range they have optimum operating regions. Dispatch schedules taking this effect into consideration can make significant savings in the valuable water in the reservoir without reducing the energy output. A methodology to optimize the dispatch schedules for Laxapana complex with special reference to Canyon power station has been developed. Sample calculations show that the water saving can be as high as 4.1%.

ACKNOWLEDGEMENT

The authors gratefully acknowledge System Control Center and DGM, Laxapana Complex, Ceylon Electricity Board for making data available for this study. General Sir John Kotelawala Defence University and the Department of Electrical Engineering, University of Moratuwa are thanked for supporting this study in various ways.

REFERENCES

Ceylon Electricity Board, Master plan for the Electricity Supply of Sri Lanka, Ceylon Electricity Board, June 1989.

Ceylon Electricity Board. Statistical Digest 2013, Ceylon Electricity Board, Sri Lanka, 2013.

Sunit Fernando, An assessment of the small hydro potential in Sri Lanka, April 1999.

CGS Gunasekara, Lanka Udawatta, Sanjeewa Witharana, Neural network based model for optimizing power generation in a cascaded hydro power generating system, ICIA Conference, Colombo, 2006.

Fuji Electric co. Ltd., Model test report of hydraulic turbine for Canyon power projct phase II, Fuji Electric Co. Ltd., Japan, June 1985.

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