OPTIMUM OPERATION OF HYDROPOWER SYSTEMS IN GHANA WHEN AKOSOMBO DAM ELEVATION IS BELOW MINIMUM DESIGN VALUE

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ABSTRACT
Hydropower plants in Ghana have suffered several low level operations within the past two decades. This paper looks at optimum operations of the plants during these low level conditions. The two hydropower plants are located along the Volta River at Akosombo and Kpong. The Akosombo plant is at the upstream such that its discharge creates available head for the Kpong plant which is downstream. The Akosombo plant is designed to operate between the levels of 75.59m minimum and 84.12m maximum while the Kpong plant operates between 14.5m and 17.7m. The mode of unit combinations for optimum power generation is determined in this paper. This could serve as a guide in operating the two Hydropower plants. The method presented could also function as a power prediction tool during the low level conditions at Akosombo (i.e. below 75.59m).

Keywords: *Hydropower, Optimum, Low level, Head, Unit combinations.*

INTRODUCTION

The Volta River Authority (VRA) operates and manages the two hydroelectric power plants in Ghana. The plants at Akosombo and Kpong were commissioned in 1965 and 1982, respectively and they provide the bulk of Ghana's electricity. The two stations account for 1,072 megawatts (MW) out of a total national power-generating capacity of 1,652 MW, with Akosombo providing 912 MW while Kpong provides 160MW. The plants are located on the Volta River with Akosombo at the upstream of Kpong.

The Akosombo plant with six units of turbine-generators operates under normal condition between 84.12m (276ft) maximum and 75.59m (248ft) minimum of headwater elevation. The Kpong plant comprises four turbine-generator units with 40MW capacity per unit making a total output of 160MW. The normal water level for operation of the plant is between 17.70m maximum and 14.50m minimum. The available head for the running of Kpong plant is built up from the discharge from the Akosombo plant.

Since the installation of the Hydropower plants at Akosombo and Kpong, there have been records of low water level periods at the Akosombo dam, which were below the minimum design condition. Those periods include the unprecedented drought of 1982-83 with a record of 71.86m on 12th June 1984 (VRA, 1996), which compelled the rationing of electricity until 1986. In August 1994, the level of Volta Lake was 72.99m. The year 1998 also recorded a low water level of 72.21m. These levels were well below the 75.59m, which is the minimum level for generating power without risk of damaging the turbines.

The objective of the paper is to develop a system for estimating an optimal power output from the hydropower system in Ghana at the low headwater elevation conditions of the Akosombo hydropower plant.

REVIEW AND OPTIMISATION TECHNIQUES

Optimisation is the process of finding the conditions that give maximum or minimum value of a function (Stoecker, 1971). Optimisation is of two levels, namely, Comparison of alternate concepts and Optimisation within a concept.

Comparison of alternate concepts is a problem mostly encountered during the designing stage. It involves deciding on an optimum design among other alternatives. Optimisation within a concept most often has to do with operational methods of a system where the most optimum output is sought. It applies to existing or already designed systems. This is the kind of problem to be dealt with in this paper.

In hydropower systems there are two related short-term optimisation problems, namely, *'unit commitment'* and *'economic dispatch'* (Power, 2002). Unit commitment is the process of deciding when and which generating units at each power station are to be started and shut down. The unit commitment problem tends to answer the question: Given that there are a number of subsets of the complete set of 'N' generating units that would satisfy the expected demand, which of these subsets should be used in order to provide the minimum operating cost (Wood, 1984). Economic dispatch is the process of deciding what the individual power outputs should be at each point in time given the scheduled generating units. It assumes that there are 'N' units already connected to the system (Power, 2002).

There is a number of hydropower optimisation software developed and are available for use. Examples of such available hydro system software are:

(i) **MICROHYP** software is an optimisation module, which uses a dynamic programming technique to choose a design, which meets the power requirements at the least possible cost (Swansea, 2002). (ii) **MaxHydro** is Hydropower Optimisation Software designed to optimize hydroelectric generation in the new deregulating market environment. MaxHydro takes into account changes in market conditions that will maximize profits from power sales while optimizing the operation and planning of the entire hydropower system (Z&M Numerics, 2002). (iii) **VALORAGUA** is software whose main objective is to determine the optimal generating strategy of a mixed hydro-thermal electric power systems. The optimal operating strategy is obtained for the system as a whole, with emphasis on the detailed simulation and optimisation of the hydro subsystem operation. (iv) **VANSIMTAP** is an integrated software package for the simulation of one or more river systems (Sintef, 2002). It is primarily aimed at hydropower production. (v) **VRASIM** (Volta River Authority Simulation Model) is a generation expansion model capable of representing both hydro and thermal plants. It can model reservoir operations, power generation and dispatch (including VRA's contract with VALCO), load growth, system additions capital and operating costs, tariffs and revenues and much more (Acres, 1992). (vi) **SISOPT** is an optimization model developed for the management and operations of the Brazilian hydropower system (Barros *et al.* 2003). This system employs, first, linearzed techniques for the basic model which was non-liner and then solved by linear programming. The problem was formulated for the normal operating conditions.

Most of the hydropower optimisation softwares and models appear to have aimed at regulating units operating at a time to satisfy power demand and in normal operating condition. The scenario to be dealt with in this paper, however, involves operation of the Akosombo and Kpong turbine units as limited by the available head at upstream reservoir when it is below the design water level.

There are several techniques for solving optimisation problems. These include mainly Linear Programming, Calculus Method, Dynamic Programming, Geometric Programming and Search Method. Technique of optimisation are considered and chosen based on the problem at hand (Denardo, 1982; Stoecker, 1971).

$$P = gn_aH_aq_a + an_kq_k - b(n_kq_k)^2 \qquad (1)$$

Where $\gamma = \rho g \eta_a$;

$$\alpha = \frac{\rho g \eta_k}{A}\left[A\left(L'_{k1} - L_{k2}\right) + tn_a q_a\right] \text{ and}$$

$$\beta = \frac{\rho g \eta_k t}{A}$$

η = total efficiency, q = discharge in m^3/s, H = head in metre, ρ= density of water (kg/m^3) g = acceleration due to gravity (equal 9,81 m/s^2), n = number of turbines, t = time in second L_1 = head water level in metres, L_2 = tail water level in metres, A = area covered by water body in m^2. Subscript 'a' refer to Akosombo plant and subscript 'k' refers to Kpong plant.

The model equation was derived from the first principle with following assumptions: Inflow into the pond of Kpong plant is solely dependent on discharge from Akosombo plant (it would not be possible to spill water from Akosombo dam when the level is below the design level and that inflow due to rainfall taken to be negligible); Out flow from the Kpong pond is only through the turbine (pond water level is not expected to rise to cause a spill of water); Power outputs and flows through the turbines at each plant are the same for each unit; and tail water levels remain constant within the period of estimate. The model is limited to low level conditions, i.e. head water level below 75.59m, with plant efficiency of 84.5% and 93.5% at Aksombo and Kpong plants respectively (Obeng and Fiagbe, 2005).

The model as given is non-linear and involves integer variables n_a and n_k. The linear programming is inapplicable due to non-linearity of the equation. Dynamic programming cannot be employed since the energy demand, which could have been a target, cannot be considered. Calculus method is inapplicable due to the integer variable that makes the equation not continuous. In consideration of geometric programming, the degree of difficulty is six, making the method not a good one. The search method of optimisation is the best applicable method. The Search technique is therefore employed in the optimisation of the system.

HYDROELECTRIC POWER PLANTS IN GHANA

The Hydroelectric power plants in Ghana consist of two plants located at Akosombo and Kpong on the Volta River in a cascaded manner. The Akosombo plant is at the upstream. Figure 1 is the schematic representation of the plants.

The available head for the Kpong plant is created mainly out of the discharge at the Akosombo plant making the number of operating units subject to amount of discharge or number of units running at the Akosombo plant.

The operation of the hydroelectric plants is influenced by two main factors; namely energy demand and the water level at Akosombo headwork. The water level limits the production capacity of the generating system. In normal op-

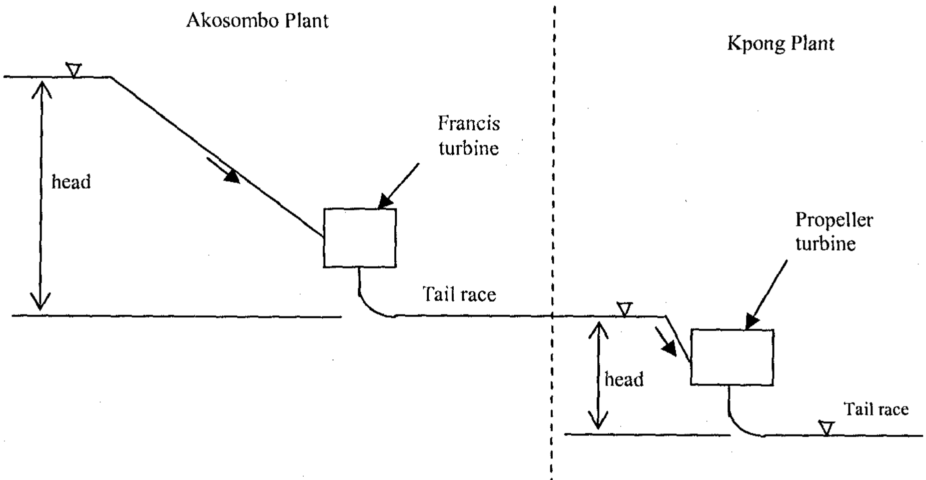


Fig 1: Schematic representation of the VRA Hydropower plants

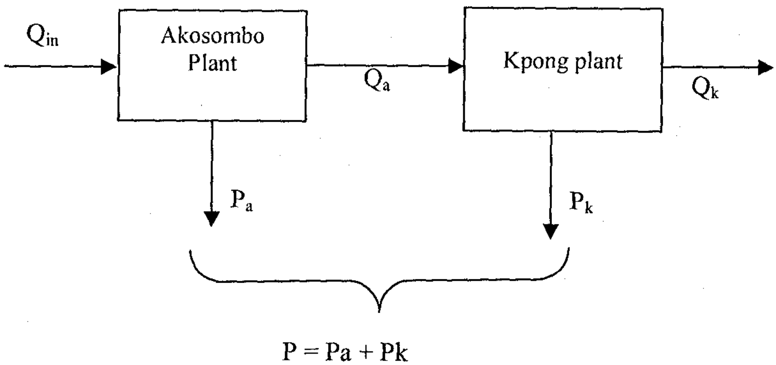


Fig. 2: Schematic states of the system

eration, the energy demand is the main criterion for operating hydropower plants. Optimisation of hydroelectric plants is mostly based on energy demand resulting in the problem of unit commitment and/or economic discharge.

The operation of the integral hydrothermal system currently is such that the thermal component of the system is operated in full capacity and supplemented with the hydro plants.

When the head water level is below 75.59m, the Akosombo plant may be operated until a minimum value of 71.93m. At this level there is the possibility of formation of vortex with air entrainment at the intake. The 71.93m level may be considered as a critical level.

THE HYDROPOWER PLANT MODEL

The mathematical model of the hydropower plants in Ghana consisting of the two plants, under the low conditions as stated in equation (1) holds for average efficiencies of 84.5% and 93.5% at Akosombo and Kpong plant respectively under the low level conditions of the Akosombo dam (Obeng and Fiagbe, 2005).

SYSTEM OPTIMISATION

The Problem: It is required to find the unit combinations of the two plants that will give the optimum power.

Input:

- Initial Lake Volta (Akosombo Dam) level,
- Initial Kpong pond level,
- Tail water level at Akosombo and Kpong plants, and
- Estimated Inflow into the Lake Volta.

Objective Function:

$$P = gn_aH_aq_a + an_kq_k - b(n_kq_k)^2 \qquad (1)$$

$$\Delta H_a = \left(\frac{Q_{in} - n_a q_a}{A_a}\right)t \leq \Delta L_a \text{ in a day} \qquad (2)$$

and $$L_1^i + \Delta H_k = L_1^i + \left(\frac{n_a q_a - n_k q_k}{A_k}\right)t \geq L_k \text{ in an hour} \qquad (3)$$

Constraints:

where Q_{in} = the inflow (m^3/s) into the Lake, L = a defined headwater level and A = the estimated area (m^2) covered by the water body, and t = time (s). Table 1 shows the area covered by the water bodies.

Output:

- Number of Turbine-generator units
- Power output
- Discharge through the plants
- Head water level expected after the period of run.

With inflow Q_{in} and outflow per unit turbine, q, for a given duration, t, the optimum power as limited by the maximum number of units with a given average efficiency is determined. The problem is divided into stages with a stage, i, having a duration of a day, so that stage i = ith day. For each stage we have power given as

$$P^i = gn^i_aH^i_aq_a + an^i_kq_k - b(n^i_kq_k)^2 \qquad (4)$$

The steps within each stage involve finding the number of units and then the optimum power output for an hour. An allowable change in the water level is assumed to vary linearly between 0.0254m (at 75.59m elevation) and 0.0038m (at 71.93m elevation) for the Akosombo Plant. A minimum level of 14.7m of head water level is set for the Kpong plant.

Table 1: Area covered by the water body of Lake Volta and Kpong pond

Lake Volta		Kpong pond	
Level /ft(m)	**Area/ km^2**	**Level /m**	**Area/ km^2**
199.5 (60.8)	2331.0	11.3	20.2
249.5 (76.1)	5766.0	12.0	24.3
259.5 (79.1)	6799.0	12.6	28.3
269.5 (82.2)	7848.0	13.4	32.4
275.5 (84.0)	8482.0	14.6	36.4
279.5 (85.2)	8897.0	15.2	38.4
		16.6	.0.8

Source: *Akosombo and Kpong Generating Station Special Studies 1982/1983, (Report No.3).*

ALGORITHM

The algorithm for solution involves the following steps:

1. Input data (head and tail water levels).
2. For stage i, set allowable decrease in head water level for Akosombo Plant, ΔH^i_a.
3. For number of units, $n^i_a = 6$ to 1
   find for a day duration the number of units to satisfy step 2

$$\Delta H^i_a = \frac{(Q_{in} - n^i_a q_a)t}{A_a}$$

   with n^i_a determine the maximum possible discharge that satisfy step 2.

4. Find net head = Head water level – Tail water level (i.e. $H^i = L^i_{a1} - L^i_{a2}$)
5. Determine new head water level. $L_{a1}^{i+1} = L^i_{a1} - DH^i_a$
6. Set minimum head water level for Kpong Plant. L^i_{k1}
7. For number of units, $n^i_k = 4$ to 1

find for an hour duration (as it is within design condition), number of units to satisfy step 6.

$$L^i_{k1} = L_{k1}^{i-1} + \frac{(n^i_a q_a - n^i_k q_k)t}{A_k}$$

   with n^i_k determine the maximum possible discharge that satisfy step 6

8. Evaluate
   a) $g = \rho g \eta_a$

   b) $\alpha = \frac{\rho g \eta_k}{A_k}\left[A_k\left(L^i_{k1} - L_{k2}\right) + t n^i_a q_a\right]$

   c) $\beta = \frac{\rho g \eta_k t}{A_k}$

   and $P^i = g n^i_a H^i_a q_a + a n^i_k q_a - b(n^i_k q_a)^2$

9. If Akosombo head water level > 236ft or day < 7 then go to next stage (i + 1) a step 2.

   The programme is coded in Visual Basic.

SAMPLE RUN RESULTS

The number of turbine units to run is influenced by the head water level as well as the inflow into the Akosombo dam. Sample runs were considered for expected inflow values of $0m^3/s$ and $62m^3/s$ (average inflow during low level period) with water levels of 75.29m, 74.68m, 73.76m, 73.15m and 72.24m (levels lower than minimum design value) at Akosombo head works and 15.0m at Kpong head works. The head of 15.0m was chosen for the Kpong plant because it is the average level during the low level periods. The results of the test are presented in Figures 3 and 4.

Expected Reservoir Inflow of 0.0m³/s

With zero or no inflow ($Q_{in} = 0$), at the head water level of 75.29m at Akosombo Dam there are 6/4 (the first figure represents units at Akosombo plant and the second units at Kpong plant) units available for operation upto 75.24m where we then have 5/4 and 5/3 units available. The units reduce to 4/3 and 4/2 at 74.58m; 3/3 and 3/2 at 73.92m. This is shown in Figure 3 together with 74.68m, 73.76m, 73.15m and 72.24m initial water levels.

Expected Reservoir Inflow of 62.0m³/s

With inflow of $62.0m^3/s$, at the head water level of 75.29m at Akosombo Dam there are 6/4 units available for operation upto 75.06m then 5/4 and 5/3 units. The units reduce to 4/3 and 4/2 at 74.42m; 3/3 and 3/2 at 73.77m. This is shown in Figure 4 together with 74.68m, 73.76m, 73.15m and 72.24m initial elevations. From the figure, we have 6/4 units at 75.29m, 5/4 and 5/3 at 75.06m, 4/3 and 4/2 at 74.42m; 3/3 and 3/2 at 73.76m; 2/2 and 2/1 at 73.12m; 1/1 and 1/0 at 72.47m.

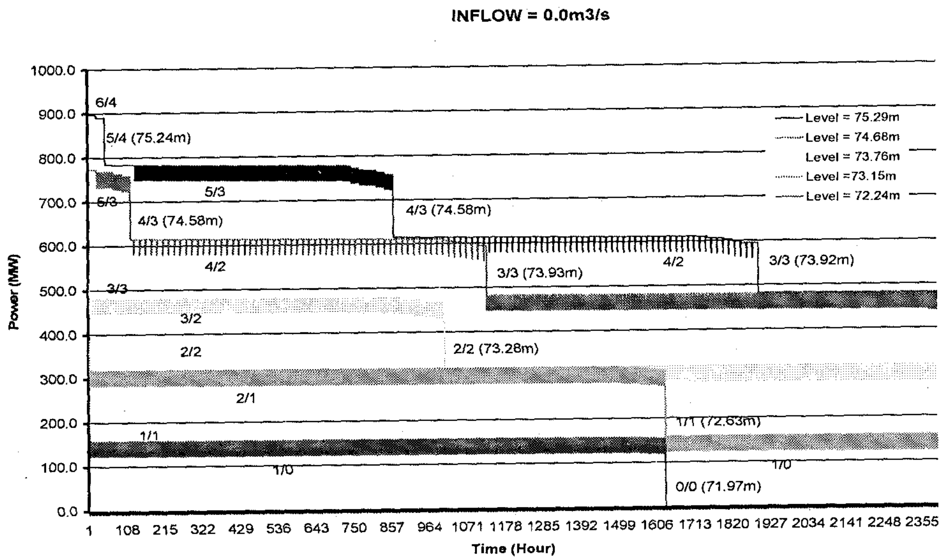


Fig. 3: Unit combinations at zero inflow

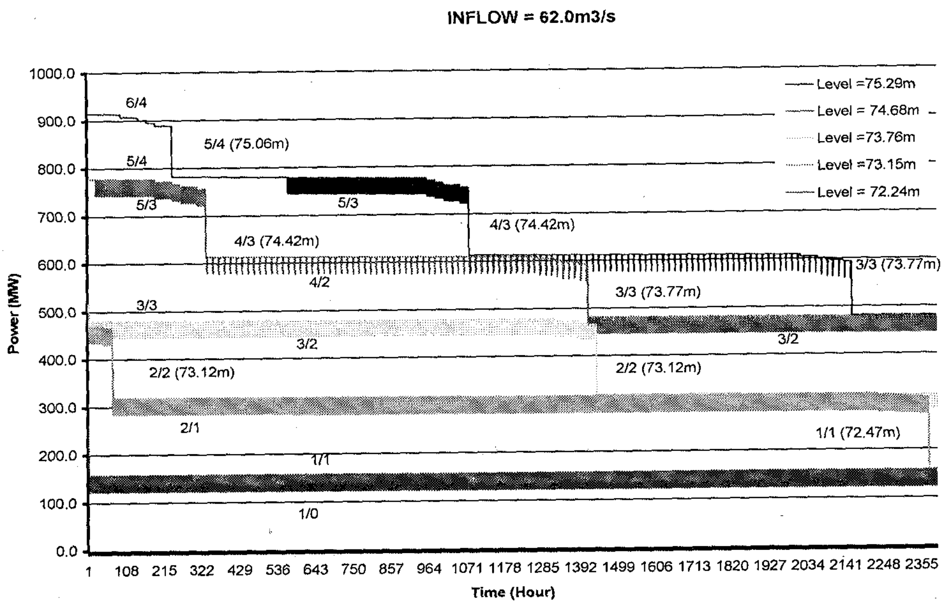


Fig. 4: Unit combinations at inflow of 62.0m^3/s

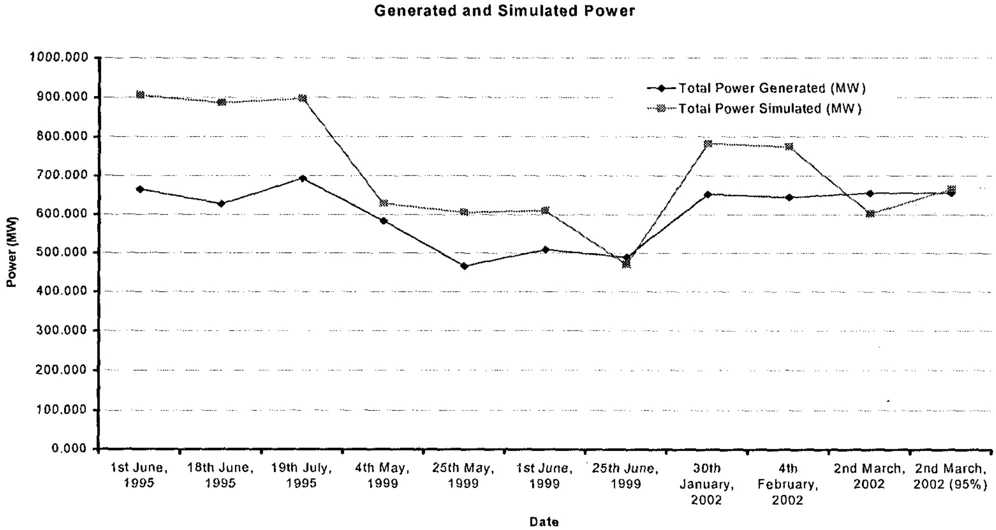
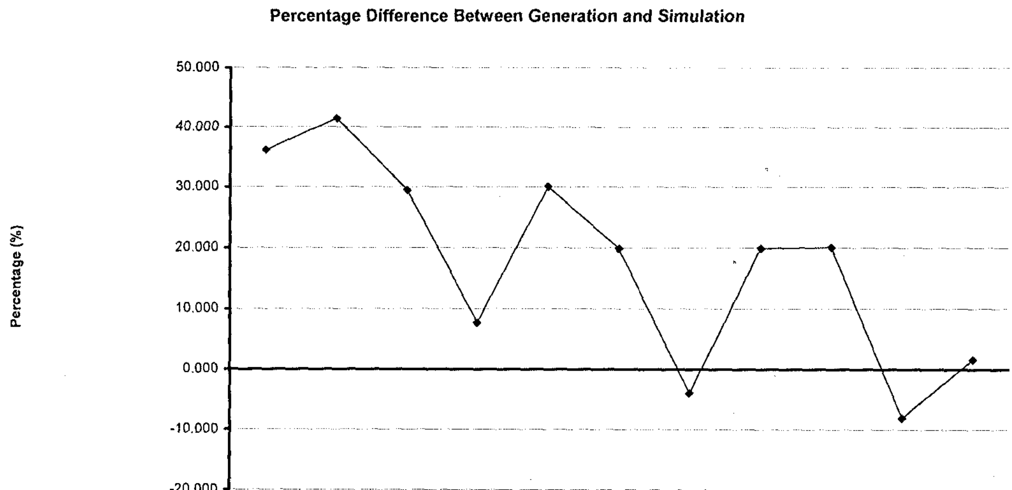


Fig. 5: Operation and Simulation Power result



	1st June, 1995	18th June, 1995	19th July, 1995	4th May, 1999	25th May, 1999	1st June, 1999	25th June, 1999	30th January, 2002	4th February, 2002	2nd March, 2002	2nd March, 2002
Percentage Increase (%)	36.114	41.429	29.460	7.758	30.052	19.838	-3.891	19.902	20.042	-8.018	1.602

Date

Fig. 6: Percentage of Simulation over Actual Operation

DISCUSSION

Power output data from operation of the plants are compared with the simulated power results and these are as presented in Figure 5. The results indicated a higher power estimate from the hydropower plants.

A decrease in headwater elevation at the Akosombo dam is assumed to vary linearly between 0.0254m (at 75.59m elevation) and 0.0038m (at 71.93m elevation). The Kpong plant pond level is limited to a minimum of 14.7m which is about the normal design headwater level. The minimum operating level is, however, 14.25m.

The operational and simulated power output results are compared in Figure 6 for the stated dates. The operation data for 1st June 1995 when the inflow was 358m^3/s, head water levels were 74.65m at Akosombo dam and 15.11m at Kpong pond, the total outputs was 665.208MW. The simulated result corresponding to these conditions is 905.925MW. This result indicates available higher power of 36% over the actual operation as shown in Figure 6. The subsequent data for the given dates also show available higher power as to what was generated with exception of 25th June 1999 and 2nd March 2002.

For 25th June 1999 the generated power output was 489.250MW whilst the simulated value was 470.211MW with a difference of 19.039MW lower i.e. 3.8%. The 2nd March 2002 result indicates an actual generated power output of 655.417MW and the simulation as 602.865MW. This is about 8% lower. The difference may be attributed to a testing program that was carried out on the retrofitted units at the Akosombo plant during the period. It was, however, found that the retrofitted units operate with better efficiency of about 95% even at the low levels at the Akosombo plant. The simulation was however at efficiency of 84.5%. The simulation at efficiency of 95% gave 665MW as compared with the 655.417MW.

CONCLUSION AND RECOMMENDATION

Optimal operation of the hydropower plants at Akosombo and Kpong, when headwater level at Akosombo dam is below minimum design level, has been carried out with application of search technique. The mode of operating the two plants by means of number of units to run at various plants has been determined for optimal power generation. Optimisation of the system is programmed with coding in Visual Basic.

The results include the number of units that can be run on hourly bases to obtain the optimum power output within given constrains. The Power output indicated is that available for the period by remaining within the stated constraints. It is advised that Kpong plant units are always maintained at peak efficiency. Figure 5 comparers given operation data to those obtained from the simulation.

The result of this paper is recommended for use as a guide in the operation of Akosombo and Kpong Hydropower plants by VRA. It may also be used to predict the available power for some period ahead. The program is developed mainly for the heads of water levels at Akosombo dam less than the normal recommended minimum of 75.59m. It is expected that by the use of this program, optimal power output shall be obtained at the low water level at Akosombo dam.

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