Dynamical Control Model of the Cascaded Kainji-Jebba Hydropower Operating Head

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Abstract— Operation and design of control system for the cascaded Kainji-Jebba hydropower system poses a great challenge to researchers and engineers. The difficulties arose from the fact that the system is affected by several nonlinear interacting factors such as variations in inflows, stochastic factors that are weather related, availability of the turbo-alternators, and numerous other constraints that are influenced by the system dynamics. All these makes the mathematical representation of the system difficult. This paper presents the development of a dynamical model for the operation and optimal control of the operating heads of the cascaded system. The mathematical models were developed from energy conversion equation and Bernoulli's equation. The model was calibrated and tuned using measured data. Upon validation by comparing the response of the model with measured head, a deviation within $\pm 2\%$ was observed, making it a good prediction of the system response and appropriate for control system design.

Keywords— Control model, Discharge, inflows, Operating head, Turbo-alternators.

1 Introduction

Hydropower generation in Nigeria is currently provided at three major locations: the Kainji hydroelectric power station (KHEPS), the Jebba hydroelectric power station (JHEPS) and the Shiroro hydroelectric power station. KHEPS and JHEPS are located on the River Niger about 103 km from each other with the latter downstream while SHEPS is built on Kaduna River in Niger State, Nigeria (Sambo, Garba, Zarma, & Gaji, 2012).

The cascaded KHEPS and JHEPS are made feasible by two reservoirs constructed on the international river, the Niger, as it wends its way finally to the Ocean. The two reservoirs differ in that the primary one at Kainji encompasses a large lake that extends from the dam to its entrance over 120 km. The secondary reservoir located at the Jebba is much smaller, less disruptive of the ecosystem yet capable of generating electric power of almost the same magnitude as its much larger counterpart (Ale et al., 2011; Jimoh, 2008).

The Jebba Reservoir depends on discharge from the Kainji power station during the black flood but during the white flood (Rainy season) some rivers downstream of Kainji flows into River Niger and hence into Jebba reservoir in addition to Kainji discharge. As a result, the Jebba reservoir is much smaller and must be operated in cascade with the Kainji reservoir. This arrangement imposes the need for better water management if the units at Jebba are to operate efficiently all the year.

The KHEPS located at $09^0 51' 45'' N$, $04^0 36' 48'' E$ has an installed capacity of installed capacity of 760 MW from 8 units of turboalternators, units 1G5 to 1G12. Units 5 and 6 are rated 120MW each, units 7, 8, 9 and 10 are rated 80 MW while units 11 and 12 are 100MW each. The JHEPS on the other hand is located 103 km downstream of the KHEPS at $09^0 08' 08'' N$, $04^0 47' 16'' E$. It was commissioned on April 13, 1985 with an installed capacity of 578.4 MW. It has has six fixed blade propeller type turboalternators, each rated at 96.4MW (Omeiza et al., 2019; Salami, 2007)

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2 Operational Characteristics of the KHEPS and JHEPS

An aspect of the problems affecting the operation of KHEPS and JHEPS in the cascade is the reliance on intuitive (trial and error) water release rules instead of scientifically motivated policies(Jimoh, 2008; Salami, 2007). KHEPS turbo-alternators have variable blades and internal governors; this allows the reservoir head to vary between 24 m and 42 m, depending on the time of the year. Clearly, under such conditions, fixed blade turbine cannot operate.

JHEPS, employs fixed bladed turbines and as a result, the head has to be maintained strictly between the range of 99 m and 103 m. Achieving this objective pose some very serious challenges to the operator since the two reservoirs are in cascade separated by 103 km and the discharge from KHEPS depends on the condition of the machine, inflow into Kainji and the rainfall in between.

Maximum rainfall between August to November of the year usually causes flooding of Kainji reservoir around September. When the spillways are opened in September during high inflows, the water flows into Jebba reservoir. Sometimes this also results in flooding of the Jebba reservoir because water also flows into it from the catchment area. During the period of low inflows from December to May, the head of water in the reservoirs often falls below the nominal level. Any attempt to operate the machines at low head usually causes vibration of the turbo-alternators (Thomas et al., 2018).

The availability of the turbo-alternators also has a direct effect on the reservoir head. Whenever a unit fails at KHEPS, it reduces the inflow into JHEPS. Operators of JHEPS may be forced to reduce the number of operating machines which in turn reduces the energy on the grid. The head at KHEPS keeps increasing and a significant percentage of the water is lost to evaporation. A reverse situation occurs when machines fail at JHEPS while KHEPS keeps releasing water, the excess water spill away instead of being utilised at KHEPS. A review of the daily report of operations from the two stations shows that there are several days when the units are shut down due to the inability to manage resources appropriately

(TCN-NCC, 2017).

To solve the optimal control problem that will maximise the energy generation in the two stations, the problem must be properly posed in a standard form (Robert & Michaud, 2011; Zheng, Fu, & Wei, 2013).

There have been various researches to model the system such as to come up with a scientifically motivated operational policy. Some are based on the statistical model of inflow observation (Using regression analysis) and the use of dynamic programming for optimal policy formulation (Aribisala, 2007; Jimoh, 2008; Salami, 2007). Such models are not suitable for dynamic system.

A time series model has also been suggested but the model formulated using this method is non-causal, hence cannot be used in control design (Ale et al., 2011; Aribisala, 2007; Nwobi-Okoye & Igboanugo, 2012).

The artificial neural network model was presented in (Abdulkadir et al., 2013; Igboanugo & Nwobi-Okoye, 2013; Salami et al., 2015), similarly the model does not leads to a real time control system design.

A more appropriate model is those involving the system dynamics. Nevertheless there have been focus on the turbine dynamic and its effect on system stability (Lu & Hogg, 2000; Nanaware, Sawant, & Jadhav, 2012). A more appropriate model should consider the reservoir dynamics, turbine dynamics and availability of the turboalternators.

The literature review carried out during this work could not find a related work that attempts to develop a control model for either or the two hydropower stations. This research, therefore, focuses on developing a control model for the two stations which can be used to determine the optimal control policies for the release of water from KHEPS such that the reservoir head at JHEPS remains relatively constant.

3 Mathematical Modelling of the KHEPS and JHEPS

As demonstrated in this Figure 1 presents the schematic representation of the two hydropower stations in cascade. The variables affecting the reservoir dynamics and power generation dynamics as a function of head are indicated. It should be noted that JHEPS has six identical units while KHEPS has three groups of units; 4 sets of 80MW, 2 sets of 100MW and 2 Sets of 120MW units. Each of these groups will have to be considered separately.

The operating parameters are also defined as listed below: h represents the water head (m), Q is the Inflow into the reservoir $(m3/s)$, q is the inflow into the penstock $(m3/s)$, Q_L represents the losses (m^3/s), Qs stands for the discharge through spill way $(m3/s)$, $A1$ is the effective surface area $(m2)$, $A2$ is the area of the inlet to the penstock $(m2)$ and $U1$ represents the turbo-alternator units.

K - Kainji
J - Jebba
1 – KHEPS Reservoir
2 – KHEPS Turbo-alternator
3 – KHEPS Penstock
4 – JHEPS Reservoir
5 – JKEPS Turbo-alternator
6 – JHEPS Penstock
7- River Channel
8 – Discharge for JHEPS

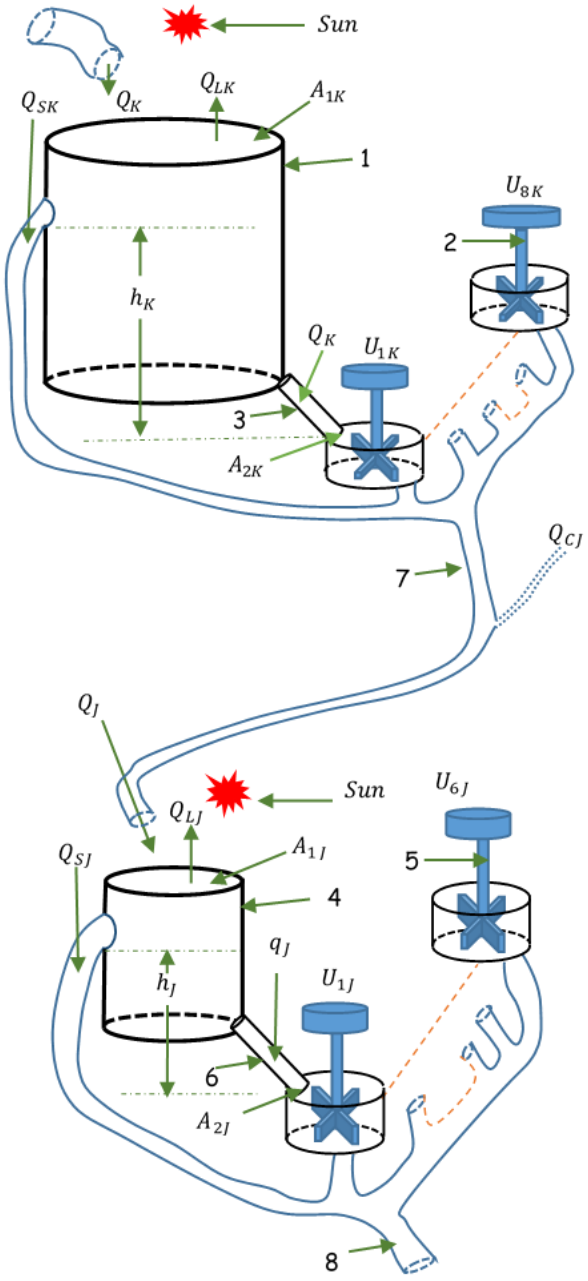


Fig. 1: Schematic Representation of Kainji-Jebba Hydroelectric Power Stations

3.1 Electric Power Generated at KHEPS and JHEPS

Given that P_e is the electrical power developed in from a hydropower plant, η represents the energy conversion efficiency, ρ is the density of water in (kg/m^3), g is the acceleration due to gravity (m/s^2), h is the operating head of the reservoir (m); and q is the flow rate in (m^3/s).

Then;

$$P_e = \eta\rho ghq \quad (1)$$

From Figure 1, the flow rate q is related to the discharge velocity by;

$$q = A_2 v_2 \quad (2)$$

A_2 is the cross-sectional area of the penstock intake (m) and v is the velocity of water (m/s).

$$P_e = \eta \rho g h A_2 v \quad (3)$$

The velocity can be express as a function of head by applying the Bernoulli's energy equation (4) to the input and output of the reservoir (White, 2015).

$$^1/_2\ \rho {v_1}^2 + \rho g h_1 + P_1 = {}^1/_2\ \rho {v_2}^2 + \rho g h_2 + P_2 \quad (4)$$

Let v_1 be the velocity at the intake and v_2 at the discharge, P_1 *and* P_2 are atmospheric pressure values at the surface and the outlet. In practice P_1 *and* P_2 are approximately equal for Kaplan low head schemes. h_2 is the head at the outlet which equals zero. Since the velocity of water at the head of the reservoir is much less than the velocity at the penstock outlet, v_2 is far greater than v_1 and equation (4) can be reduced to the form in equation (5) (Guo et al., 2009; Kyung et al., 2010):

$$\rho g h_1 = {}^1/_2\ \rho {v_2}^2 \quad (5)$$

$$v_2 = \sqrt{2 g h_1} \quad (6)$$

$$q = A_2 \sqrt{2gh} \quad (7)$$

$$P_e = \sqrt{2}\, \eta \rho A_2\, g^{3/2}\, h^{3/2} \quad (8)$$

$$P_e = \beta \eta h^{3/2} \quad (9)$$

where $\beta = \sqrt{2}\, \rho A_2\, g^{3/2}$

The three groups of units at KHEPS can be represented as follows: n_{1K} stands for 4 sets of 80 MW units, n_{2K} stands for the 2 sets of 100 MW, while n_{3K} represents the two sets of 120 MW. Hence the electric power generated at KHEPS is represented by equation (10).

$$P_K = \left(\sqrt{2}\ n_{1K}\, \eta_{1K}\, \rho\, A_{2K} g^{3/2}\right) {h_K}^{3/2} + \left(\sqrt{2}\ n_{2K}\, \eta_{2K}\, \rho\, A_{2K}\, g^{3/2}\right) {h_K}^{3/2} + \left(\sqrt{2}\ n_{3K}\, \eta_{3K}\, \rho\, A_{2K}\, g^{3/2}\right) {h_K}^{3/2} \quad (10)$$

$$P_K = \beta_K n_{1K} \eta_{1K} h_K^{3/2} + \beta_K n_{2K} \eta_{2K} h_K^{3/2} + \beta_K n_{3K} \eta_{3K} h_K^{3/2} \quad (11)$$

JHEPS has 6 identical units and they are designated by n_J.

$$P_J = \left(\sqrt{2}\ n_J\, \eta_J\, \rho\, A_{2J} g^{3/2}\right) {h_J}^{3/2} \quad (12)$$

$$P_J = \beta_J n_J \eta_J\, h_J^{3/2} \quad (13)$$

Therefore, the total power generated from the cascade system (P_T) is as follows:

$$P_T = P_K + P_J \quad (14)$$

$$P_T = \beta_K n_{1K} \eta_{1K} h_K^{3/2} + \beta_K n_{2K} \eta_{2K} h_K^{3/2} + \beta_K n_{3K} \eta_{3K} h_K^{3/2} + \beta_J n_J \eta_J\, h_J^{3/2}$$

$$P_T = (\Psi_{1K} + \Psi_{2K} + \Psi_{3K})\, h_K^{3/2} + \Psi_J\, h_J^{3/2} \quad (15)$$

$$\Psi_{iK} = \beta_K n_{iK} \eta_{iK};\ i = \{1 \dots \dots 3\}$$

$$\Psi_J = \beta_J\, n_J\, \eta_J$$

Equation (15) represents the power generated, indicating that it depends on the reservoir head and number of operating units. Consequently, the dynamical model of hydropower station is determined by the dynamical consideration of both the alternator and reservoir operating head.

3.2 Dynamical Head Equations for the KHEPS and JHEPS Reservoirs

Consider the KHEPS reservoir as represented in Figure 1 with Q as the inflow and q as the outflow;

$$A_{1K} \frac{dh_K}{dt} = Q_K - Q_{LK} - Q_{SK} - q_{2K} = Q_K - Q_{LK} - Q_{SK} - A_{2K} v_{2K} \quad (16)$$

Equation (16) can be combined with equation (6) to give:

$$A_{1K} \frac{dh_K}{dt} = Q_K - Q_{LK} - Q_{SK} - \sqrt{2 g h_K}\ A_{2K} \quad (17)$$

$$\frac{dh_K}{dt} = -\left(\frac{A_{2K}}{A_{1K}} \sqrt{2g}\right) {h_K}^{1/2} + \frac{1}{A_{1K}} (Q_K - Q_{LK} - Q_{SK}) \quad (18)$$

Hence, the dynamical model for KHEPS with n_K number of units is expressed as:

$$\frac{dh_K(t)}{dt} = -\, n_K \propto_K h_K^{1/2}(t) + \mu_K (Q_K(t) - Q_{LK}(t) - Q_{sK}(t)) \quad (19)$$

$$\propto_K = \sqrt{2g}\ {A_{1K}}^{-1} A_{2K} \quad \text{and} \quad \mu_K = {A_{1K}}^{-1}$$

The dynamical model for JHEPS with n_J number of units and $Q_{CJ}(t)$ (the inflow from the catchment area in-between the two reservoirs) can be expressed as:

$$\frac{dh_J(t)}{dt} = -\, n_J \propto_J h_J^{1/2}(t) + \mu_J (Q_J(t) - Q_{LJ}(t) - Q_{sJ}(t)) \quad (20)$$

Where $Q_J = q_k + Q_{sk} + Q_{CJ}$

Combining equations (19) and (20) gives the JHEPS model as presented in (21).

$$\frac{dh_J(t)}{dt} = -\, n_J \propto_J h_J^{1/2}(t) + \mu_J ((q_k(t) + Q_{sk}(t)) + Q_{CJ}(t) - Q_{LJ}(t) - Q_{sJ}(t)) \quad (21)$$

where $\propto_J = \sqrt{2g}\ {A_{1J}}^{-1} A_{2J}$ and $\mu_J = {A_{1J}}^{-1}$.

Equations (19) and (20) can be written in the formal approach for a nonlinear control system as presented in equation (22).

$$\frac{d}{dt}\mathbf{x}(t) = f[\mathbf{x}(t), \boldsymbol{u}(t)] \quad (22)$$

$$\mathbf{x} = [x_1\ x_2]^T \text{ and } \mathbf{u}(t) = [u_1\ u_2]^T$$

where $x_1 = h_k, x_2 = h_J, u_1 = Q_k, u_2 = Q_J$ and $u =$

$net\ inflow\ Q$,

3.3 Estimation of Model Parameters

If observations of the inflow and head are studied such that a section of time where the behavior of the system is almost linear is selected. If $Q_{(t)}$ is the net inflow in (m^3/s), $q_{(t)}$ is the discharge in (m^3/s) and Δh is the change in head between time t_1 and t_n, then;

$$A_1 = \frac{1}{\Delta h}\int_{t_1}^{t_n}(Q_{(t)} - q_{(t)})\,dt \qquad (23)$$

Equation (21) was applied to a measured data to obtain:

$A_{1k} = 883{,}208{,}571.43\ m^2$ and

$A_{1j} = 287{,}775{,}000\ m^2$.

The effective area of the scroll casing can also be estimated from the observation. This is motivated by the fact that

$$A_{2i} = \frac{1}{n_i\sqrt{2gh_i}}q_i,\ for\ i = 1,2,3,\ldots,365 \qquad (24)$$

Hence given the observation for a whole year, the median value of A_{2i} was used as A_2 in the model. Where n_i represents the number of operating units on day i, q_i is the total station discharge on day i.

In estimating the effective area of the scroll casing (A_2) for KHEPS and JHEPS, the area was calculated per day using equation (24) from 1st of Jan. to 31st of Dec. 2013. The calculated values were modelled and the median in each case was estimated as:

$A_{2k} = 8.55005\ m^2$ and $A_{2j} = 13.53289\ m^2$

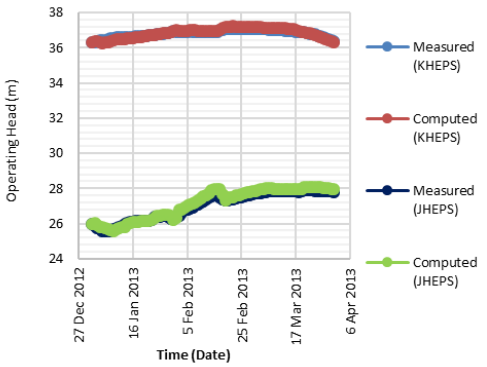
The evaporation loss used in this model was estimated from observations between 1974 and 2009 for KHEPS and 1985-2010 for JHEPS. Monthly maximum, minimum and average evaporation loss were plotted in each case. The average value was mathematically modelled and presented as:

$$Q_{evp,K} = 0.0003t^6 - 0.0126t^5 + 0.0845t^4 + 1.8323t^3 - 25.699t^2 + 88.123t + 7.267 \qquad (25)$$

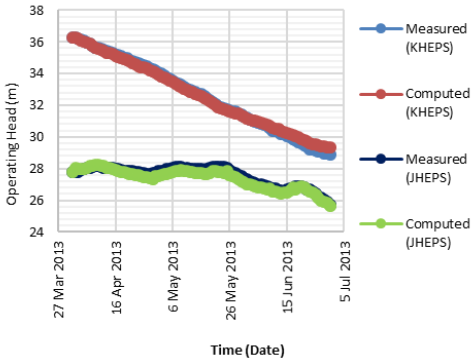
$$Q_{evp,\ J} = 0.0003t^6 - 0.0126t^5 + 0.0845t^4 + 1.8323t^3 - 25.699t^2 + 88.123t + 7.267 \qquad (26)$$

4 Model Validation of the Cascaded KHEPS and JHEPS using Observations

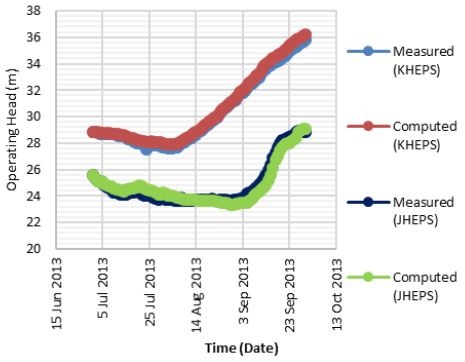
The model was validated subject to the fact that the two stations are connected through the channel such that the inflow into JHEPS is equal to the sum of the discharge from KHEPS, spill from KHEPS and the flow from tributaries along the connected channel. A comparison between the measured head and the computed head for year 2013 is as presented in Figure 2 (a) to (d). The inflows and the number of operating machines per day were passed into the model in addition to the system parameters: effective surface area, effective scroll casing area and the evaporation. The results show a good agreement between the measured and computed head in each case. An error within $\pm 2\%$ was observed, making the model a good prediction of the system response and appropriate for control system design. The slight deviation is as a result of the estimated value used in the system parameters and the approximation errors from the numerical solution to the model.



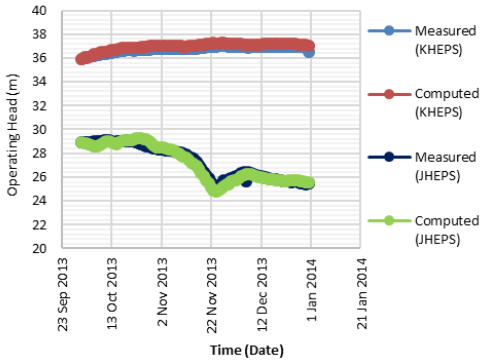
(a) Jan.- Mar.



(b) April. - Jun.



(c) Jul.- Sep.



(d) Oct.- Dec.

Fig. 2: Comparison of Observed Head with Computed Head for the Cascade KHEPS and JHEPS in 2013

5 CONCLUSION

A model for nonlinear control system design and analysis for the cascaded KHEPS and JHEPS has been presented in this paper. The dynamical models were developed from flow continuity conditions. The developed model, together with the optimal control algorithms will work well to provide a more dependable scheme for the operators. This will boost the generation potential of the cascaded power system and ensure safe operation such that the operating heads are kept within limits.

For future research, we recommend that the turbine dynamics should be embedded in the equation to replace the conversion efficiency. Also, it is recommended that a similar work should be carried out on the Shiroro hydropower station, to aid research in ensuring the operation of the station throughout the year.

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