

A Study of Energy Conversion at the Jebba Hydroelectric Power Station

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Abstract - Hydroelectric power significantly contributes to the national power grid of Nigeria. This paper examined the extent of utilization of the energy supplied into each of the turbo-alternators at the Jebba Hydroelectric Power Station (JHEPS), Nigeria and suggests corrective culture to be employed for an improved efficiency. The basic principle of a hydropower scheme and its conversion considerations were highlighted. The daily discharge, Q , in cumecs and the power generated, P , in MW at JHEPS over a decade period (2005 – 2014) were analyzed using codes and scripts of Microsoft EXCEL-VBA. Jebba hydroelectric power station is one of the three major hydropower stations in Nigeria and the potential is just beginning to be exploited. The stochastic distribution pattern of the station is also presented for further analysis of failure and repair of the station.

The conversion behavior of each unit was found to be linear and all have a value greater than 0.5 on a scale of 0.00 to 1.00. Turbo-alternator (TA) unit 1 was found to have the highest conversion characteristic of 0.9951, while unit 4 was the least at 0.6884. However unit 6 was exempted in this analysis as it was not in use during this period. The paper also gave an insight into the effective operating head of each TA, the paper also suggests the corrective measure to employ for each turbine.

Keywords - Turbo-alternator; Hydroelectric power; Conversion; Flow rate; Penstock.

I. INTRODUCTION

Nigeria is a developing nation and aspiring to be one of the top twenty (20) nations with the most stable economies in the World by the year 2020, therefore sustainable electrical power supply becomes imperative and requires rapt attention of the government and private stakeholders, to keep this aspiration in line.

A hydroelectric station might require a huge startup cost, but in most cases, it is typically a durable one and with a relatively low maintenance cost [1].

Hydropower schemes use energy derived from moving water to create rotational motion which in turns drive a turbine connected to an alternator. The connection between the turbine and the alternator can be horizontal or vertical, this combo is called “turbo-alternator”. Hydropower schemes contribute about 29% of the Nigeria National grid [2]. The Jebba Hydroelectric Power Station (JHEPS) is one of the three main Hydropower sources in the country. JHEPS fully commissioned in 1985, is located in Jebba, Niger State, on the latitude of $9^{\circ}08' N$ and longitude of $4^{\circ}49' E$ [3], approximately 350 km away from Lagos. The present state of power generation manifests unpleasant variations that could benefit from a systematic study if the present poor condition is to be significantly improved.

JHEPS has six generating units rated at 96.4 MW each (a total of 578.4 MW), each turbo-alternator has a synchronous speed of 93.75 rpm [4]. Fig. 1 shows the arrangement of the six units at JHEPS.



Fig. 1: Arrangement of JHEPS alternator Units

The major source of inflow into the Jebba reservoir is from the Kainji dam, which makes it possible to generate throughout the year. JHEPS is a low-head hydropower

facility with a head of 27.6 metres and fast flow rate of about 380m³/s. JHEPS has six reaction Kaplan type turbines, each using a five-bladed runner directly coupled vertically to compatible alternators to give turbo-alternators rated at 119 MVA each [5].

The value of the efficiency of a turbine gives how the energy supplied to the turbine is being utilized, the closeness of the value to unity (1.00) gives how much of the input energy (E) converted to a useful work. This value helps the management to take the necessary decision in their operation. Conversion behaviour here is an ‘*efficiency follower*’ on the other hand, it means the higher the value, the higher the efficiency and vice versa. Conversion behaviour instead of efficiency is used here because of the unascertained value of the losses in the penstock. However, the two values are parallel and could be used for same analysis.

Maruf A. [6] estimated the average operational efficiency of the JHEPS to be 89.43%, this was estimated using the data of the year 2010 only [6]. This paper beyond this scope, and also, the actual efficiency could not be ascertained due to inadequacy of hydraulic losses and other uncertainties not taken into cognizance. TS Abdulkadir applied Artificial Neural Network to forecast the reservoir storage of the dam for the purpose of future management and usage; the training yielded a forecast of 95% with a coefficient of correlation of 0.64 [7]. This work suggest more specific management practice and is of individual unit rather than the entire station, because the continued ability to generate power depends more on individual performance rather than gross considerations and will reveal more pragmatic approaches for a sustainable operation.

It is expedient to examine the conversion ability or behaviour of a machine or an engineering system that has been in operation for a long period of time, this could help in the management decision policies, whether to maintain, retrofit or overhaul the system.

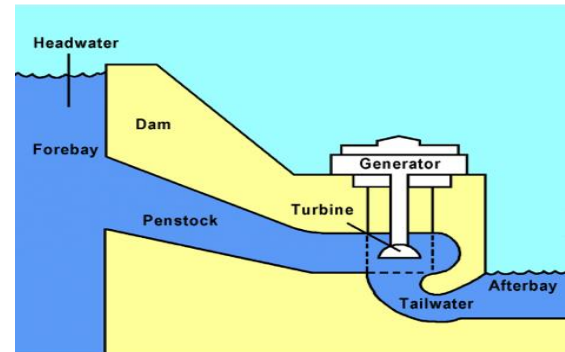
This paper examined the energy conversion behaviour of the six turbo-alternators at the JHEPS. A decade data is used to give high accuracy than similar previous works using just a year information, each turbo-alternator was considered individual unlike the previous works that examined the station as single entity as this gave clear information on each turbine. This work also studies the stochastic nature of each TA for the analysis of failure of the station.

II.

A. Physical Configuration and Basic Principle of Hydraulic Energy Conversion

Hydropower is a system driven by the power obtained from flowing water especially when it flows through a narrow channel. A hydroelectric power plant is a station where turbines are driven by mechanical energy produced by water action which then subsequently drives a generator (turbo-generator); the source of the water can be natural waterfalls or artificial waterfalls/dam [8].

A typical layout of a hydropower station is shown in Fig. 2. The dam creates a “head” or height from which water flows. A pipe (penstock) carries the water from the reservoir to the turbine. The fast-moving water turns the turbine blades which in turn rotates the shaft, the moving part of the turbo-generator [8]. Due to the action of the turbines on the shaft bearing an armature, electricity is induced according to Faraday’s law of electromagnetic induction [9].



B. Problem Formulation

The efficiency of a hydropower station can be described as the follower of the conversion behaviour, the difference between these two parameters the consideration of all the losses in the calculation of efficiency. The characteristic estimated here is a real follower of the turbine efficiency, it is a real one because it was estimated based on the measured parameters of the turbine [10].

Using Bernoulli’s principle as a basis to model the energy conversion. It states that the sum of the kinetic energy (E_k), gravitational potential energy (E_p) and the internal energy (E_{it}) on a flowing fluid of a fixed mass is constant at any point [11]. The principle also explains that a fluid with high velocity has a low pressure and vice versa. The internal energy is the work that must be done to overcome the pressure P that exists along the water path.

$$E = E_k + E_p + E_{it} = k(\text{constant}) [8] \quad (1)$$

$$E = \frac{1}{2} \Delta m v^2 + \Delta m g h + P \Delta v = k \quad (2)$$

where:

Δm is an integral mass (in kg) of the water into the penstock

v is the velocity (in m/s) of the water, Δv is an integral value of v .

h , is the height (in m) of the water is flowing through, and P is the pressure (in N/m²) on the water

g is the acceleration due to gravity (in m/s²), g is a constant value

Since $\Delta m = \rho \Delta v$, dividing equation (2) by Δv yields:

$$P + \frac{1}{2} \rho v^2 + \rho g h = k \quad (3)$$

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

Where; ρ is the density of water, (1000 kgm⁻³)

From equation (4.0), the energy possessed by the falling water through the head, h , is passed to the turbine, where it is converted into kinetic/rotational energy of a shaft.

C. The Conversion Behaviour

This involves calculating the total energy available from the reservoir. In particular it is bounded by the terms of the product which is the total energy available and may be expressed as follows.

Assigning E [in MW] as the value of the measured energy output of a TA j at an instance

$$E_{Total} = \rho g \sum_{i=1}^n h_i Q_i \quad (5)$$

$$E_{TotalJHEPS} = \rho g \sum_{j=1}^m \sum_{i=1}^n h_{ji} Q_{ji} \quad (6)$$

$j = 1, 2, \dots m$

$i = 1, 2, \dots n$

The value of E in equation (5) and (6) needs to be divided by 24 hours to have the result in MW.

m is the number of TA in consideration, while n is the number of days in analysis

$m = 5$, while $n = 3652$ (10 years)

Given SSE_{hj} as the Sum of Square Error estimated from a 10 year energy output of a TA j , to estimate the optimum value of h_o for the j th TA.

$$h_{o(optimum)} = h_o [SSE_{min}] \quad (7)$$

SSE , is estimated for each TA using a MATLAB m-file to create a toolbox.

$$E'_{ji} = \rho g (h_{ji} - h_{0ji}) Q_{ji} \quad (8)$$

$$E'_{ji} \triangleleft E_{ji} \forall i = 1, 2, 3, \dots n \quad (9)$$

Let the **conversion behaviour** of a j th TA be η ,

$$E'_{ji} = \eta E_{ji} \quad (10)$$

E'_{ji} , is the exact estimated value of the output from a given TA, j at any instance

Equation 10 shows the conversion behavior of the electrical energy output given the input.

A VBA Script tool was developed to compute the values of the variable E'_{ji} using the measured values of the constituent variables and the estimated h_o .

Measurement of variables over a decade were collected, some from the National Control Center (NCC), Osogbo, Nigeria, while some were obtained from the JEHEPS itself. The period of the data considered spanned from the year 2005 to 2014.

A plot of P_{ij} versus E_{ji} was constructed in MATLAB and EXCEL environment. In passing, it can be noted that a TA that is deteriorating with age will likely manifest decreasing value of efficiency and this will be visible from the curve. Also it should be possible to check the coefficient of correlation of the two variables. If the coefficient of correlation is significantly different from 1, then the curve will have deviated from the linear form and it would then give a curve indicative of possibly reducing overall efficiency.

III. RESULTS AND DISCUSSION

As earlier stated, a key feature to evaluate the performance of a turbo-alternator is its ability to convert energy without a discernible deterioration over the period in question. Indeed, if the rate of conversion remains relatively constant, a TA can be refurbished or repaired if in a down state. The relationships between the supplied energy and those generated for the first 5 units at JHEPS were shown in Figures 3 to 7. The correlation between the effective daily power generated was studied with respect to the potential energy made available for conversion to each TA unit. The linearity of the relationship was studied. A useful unit will tend to consistently convert equal amount of energy to equal electrical output or provide a linear relationship.

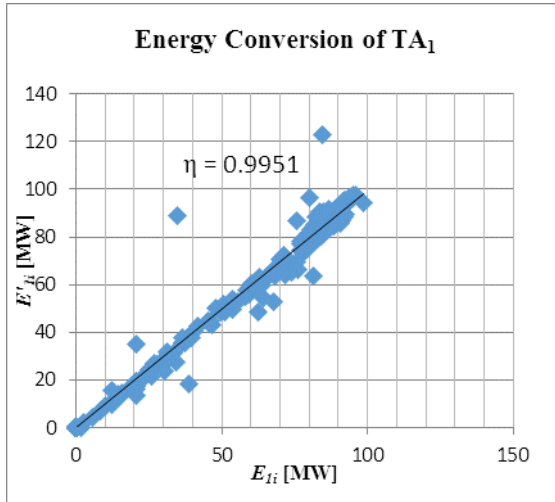


Fig. 3: Conversion Study of TA 1

This unit is seen to be converting 90% of its input energy to a useful form on the average. The most correlative points were observed to be period of July to early November. The machine was also observed to have most of its distribution close to the rated value.

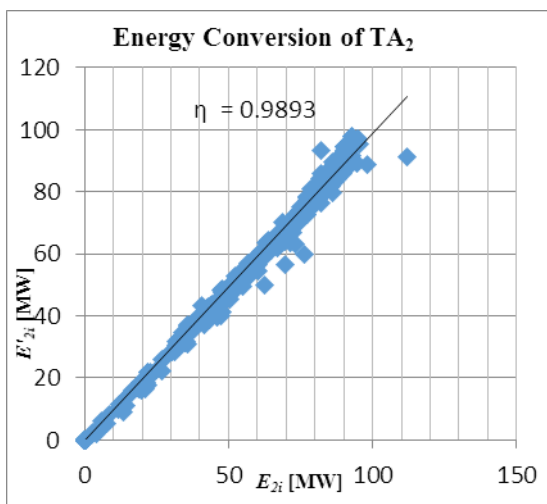


Fig. 4: Conversion Study of TA 2

This turbine seems to have over 95% of its input converted to useful work for most of the period of study, it was also noticed that the actual mass volume of water to the turbine blade is less the value of Q in the penstock, this is due to the loss. The nature of conversion appear to be uniform over the period.

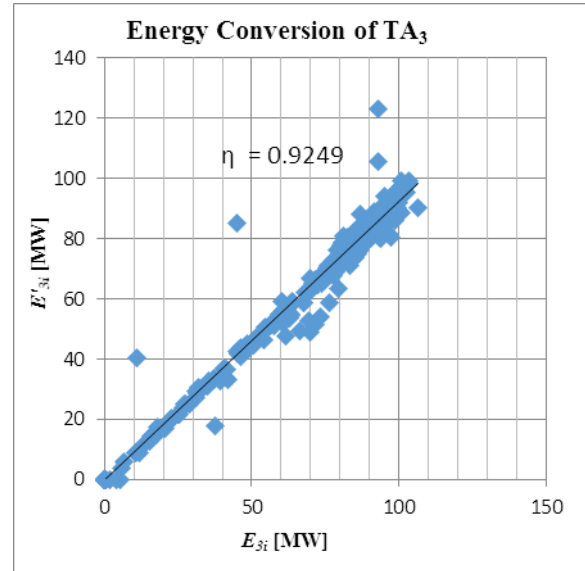


Fig. 5: Conversion Study of TA 3

This TA was observed to be efficient but still generating energy below its rated capacity. About 30% of the energy input to the turbine was underutilized.

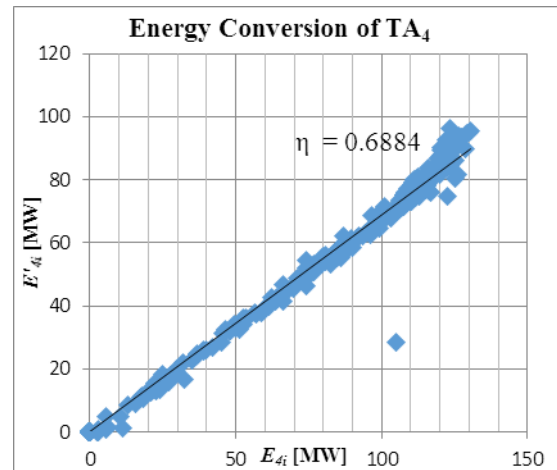


Fig. 6: Conversion Study of TA 4

This turbine is seen to be functioning much below the rated value through the period of study. On the average, 65% of the input to the turbine is being utilized. This unit of the station might need to be retrofit for better performance as it is seen to be still much in its useful life of operation.

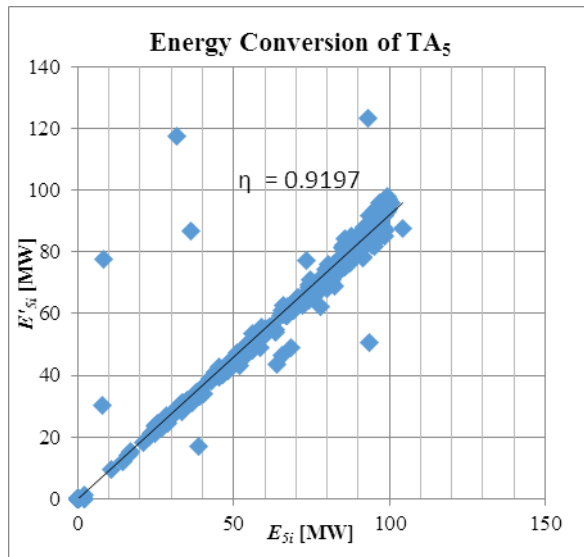


Fig. 7: Conversion Study of TA 5

This turbo-alternator appears to be productive, but some of its energy generated is not linear with the input, some management practice is suggested to be carried out. This practices might include ensuring smooth running in the penstock and the proper closure of the scroll case.

It was observed that the coordinates were cluttered much at the upper part of the plot, this signified that the machines still operate at the higher output.

The conversion characteristics of unit 1 to 5 are 0.9951, 0.9893, 0.9249, 0.6884 and 0.9197 respectively. Turbo-alternator of unit 1 shows the highest conversion efficiency with a value of 0.9951, and the least was that of unit 4 with a value of 0.6884. The peak generation during the period in consideration (2005 to 2014) is still much less than the rated value of the station. With these values of conversion characteristic of each TA unit, the output of the station can be greatly improved, some need routine maintenance while others need retrofitting.

Turbo-alternator Efficiency

From equation (10), assuming all losses are taken care of, then $\eta \equiv \eta'$, gives the efficiency of each turbine and this can also be read from equation (10)

The curves in figures 3 to 7 show that the turbine are still performing efficiently, but generating energy below the rated values. The efficiency was observed to be improved after each maintenance activity.

IV. CONCLUSION AND RECOMMENDATIONS

It was observed that the trend of energy conversion characteristic of JHEPS remains unchanged (i.e. a straight line relation); it is found to be linear, which is satisfactory and guarantees assurance of a continuity in operation of the station.

With the observation in section 3 of this paper, the following recommendations are suggested for the improved performance of the station.

Proper instrumentation should be put in place for accurate and detailed measurements, a 24-hour measuring techniques should be put in place for the measurement of the flow rate, and such readings should be collected on hourly basis.

The Power generated should be recorded on hourly basis as to aid more accurate analysis.

The turbo-alternator in the unit 4 should be retrofitted, the turbine scroll case should be isolated for replacement. Units 2 and 5 should be scheduled for complete maintenance exercise, this should include, the turbine blade and scroll case.

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