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Performance Evaluation of a Hydro-Power Plant

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Abstract: The electrical power generation of any country drives the economy of that country. Sufficient electrical power supply plays an important role for industrial development and growth of any country. The epileptic state of electricity supply in Nigeria arising partly from power generation plants' inability to operate at installed capacity led to the investigation and evaluation of hydro – power plant operational performances in a bid to suggest ways the generation capacity of these plants can be well utilized. This study evaluated the performance of Shiroro Hydro-Power Plant on monthly basis employing the relevant fluid mechanics models; the appropriate performance indices such as plant efficiency, capacity factor, utilization factor and overall efficiency were evaluated. Data obtained from the plant inventory records include daily power generation, daily hydrological data such as water discharge rate and gross operating head. The net head, the hydraulic power and the theoretical power developed by the flowing water were estimated to aid the evaluation of the plant performance indices. The results of the study for the period under review showed that the plant efficiency for 2019 varied from 43.56% to 85.83% with an average of 65.65% and 41.81% to 86.66% with an average of 65.99% for 2020. The capacity factor of the plant for 2019 varied from 25.74% to 66.78% with an average of 47.85% and 22.65% to 67.15% with an average of 49.44% for 2020 against standard practices of 50% to 80%. The plant utilization factor for 2019 varied from 42.51% to 79.95% with an average of 66.1% and 29.38% to 73.35% with an average of 62.44% for 2020 against standard practices of over 95%. From these results, it can be concluded that the generating plants were underutilized. This is due to inadequate routine maintenance, equipment fault development, low load demand from the national grid and low headwater elevation (water drought). Evaluation of the overall efficiency of the plant showed an average of 55.74% for 2019 and an average of 56.02% for 2020 against standard practices of 80% and above. This indicated a shortfall of 24.26% and 23.98% and above of energy conversion from the hydraulic power developed by the falling water. Also, out of the 600MW installed capacity and a possible energy consumption of 5,270,400MWh annually, only 2,520,243MWh of energy was consumed from the plant for 2019 and 2,606,206MWh for 2020. The overall results revealed that the potential capacity of the generating plant remains unutilized. Measures to improve the performance indices and overall efficiency of the plant have been suggested in this study.
Keywords: Hydraulic Power, Plant Efficiency, Overall Efficiency, Capacity Factor, Utilization Factor.

I. INTRODUCTION

Hydro-power is energy obtained from falling or fast-running water that can be captured for practical activity. It is currently the most common renewable energy source and contributes significantly to worldwide power generation (International Energy Agency, 2010). Hydro-power is defined by Kaunda *et al*. (2012) as the rate at which hydraulic energy is extracted from a certain amount of falling water as a result of its velocity, position, or both. The rate of change in angular momentum of falling water, its pressure, or both on the turbine blade surfaces cause a differential force on the turbine runner, creating rotary motion. Hydro-power plants are commonly utilized to generate electricity. Generation of electricity by hydroelectric power plants is one of the cleanest ways to generate electricity. Turbines embedded in the flow of water absorb kinetic energy and convert it to mechanical energy to generate hydroelectricity. The electrical power generation of any country serves as an engine that drives the economy of such country. Sufficient electrical power supply plays an important role for industrial development and growth of any country. Nigeria is endowed with large oil, gas, hydro and solar resources, and it has the capacity to generate 12,522MW of electricity from existing plants. In most days, however, it is only able to dispatch around 4,000MW, which is insufficient for a country of over 195 million people (Power Africa Company, 2021). Recent studies show that most of the hydro-power stations in Nigeria are operating below installed capacity which contributes to the epileptic electrical power supply in the country. This study considers the performance evaluation of Shiroro hydro-power plant for the reviewed period 2019 – 2020 on a monthly basis. The considered performance indices for this evaluation are plant efficiency, overall efficiency, capacity factor and utilization factor.

The lack of energy has had a negative impact on the country's business operations. Consumers of electricity must seek alternate energy sources, primarily by purchasing gas and diesel-powered generators, which are rather costly, and most enterprises that employ them incur significant production expenses.

Also, according to Asu (2017) the continued over reliance on gas and diesel-powered generators for electricity supply constitutes a major threat to the nation climate change plan. Recent statistics on the use of generating sets in the country showed that about 60 million Nigerians spend a whopping sum of ₦1.6 trillion on purchase and maintenance of generators every year (Omomo, 2018). Experts have projected Nigeria's electricity demand to hit about 395,870.20MW by 2032 (Idoniboyeobu *et al.,* 2018). This is an indication of a possible, severe and escalating energy crisis in the nearest future.

However, the Nigerian government has developed different sustainable energy policy documents to invest in the vast renewable energy potential in the country which include solar, wind, biomass and hydro under electricity vision 30:30:30 which targets generation of at least 30,000MW of power by the year 2030 with 30% of generation from renewable energy technologies (National Council on Power, 2016). Exploration of these potentials and large-scale generation of renewable energy would considerably improve Nigeria's electricity grid and alleviate power shortages. Thus, this study evaluates the performance of hydro-power plant using Shiroro hydro-power station in Nigeria as a case study with the aim of ascertaining capacity factor, utilization factor, plant efficiency and overall efficiency of the plant at different generated loads using Matlab program.

II. LITERATURE REVIEW

Studies carried out in the past have contributed in broadening knowledge relating to hydro-power plants. For instance, the study by Nwobi-Okoyea and Igboanugo (2012) which focused on the use of transfer function modeling to design a new and better approach of analyzing the performance of hydropower producing facilities in order to improve their performance. That study employed 10 years of input–output data from a hydropower generation process to build transfer function models of the process, which were used as performance indicators. According to the results, the power generation facility's efficiency was lowest in 2006 and highest in 2003. According to them, the findings of this study would open up new avenues for enhancing the maintenance effectiveness and operational efficiency of power producing facilities.

Acakpovi *et al.* (2014) reviewed existing hydro-power plant models. The study carried out hydropower plant simulation that included a model of a hydraulic turbine, governor, and synchronous machine, all of which were simulated using MATLAB software. A three-phase-to-ground fault was created in the model at t=0.2s and removed at t=0.4s, demonstrating that the generated voltage immediately regained stability due to the high excitation voltage maintained by the hydraulic turbine model's Proportional–Integral–Derivative (PID) control system. They stated that the motor speed stabilized, but that it was slower than the voltage. The simulation findings indicated a flawless generation of energy from hydropower plants that was resilient enough to withstand defects, they concluded.

Another study was carried out by Nasir (2014) on Micro-hydroelectric power plant design considerations. A MATLAB Simulink computer program was used in his work to determine all of the design parameters for the micro-hydro power plant. He stated that turbine power and speed were proportional to site head, head losses in the penstock vary from 5 to 10% of gross head, turbine efficiency ranged from 80 to 95 percent depending on the turbine type, and that generator efficiency was around 90%. He came to the conclusion that the project location was suitable for the building of a micro-hydroelectric plant.

Project efficiency, plant outage, and utilization factor were used by Jyoti and Prasad (2007) to analyze the performance of five micro hydro-power plants. Plant outage and utilization factor values were determined to be low. They pinpointed the sources of the problem and proposed solutions.

Due to the exploitable potential of hydro-power as a means of improving Nigeria's capacity in electricity generation, calls have been made for more researches so as to enhance the performance of existing hydro-power plants that would further provide framework for harnessing maximum power from potential hydro-power sites. This study therefore used the Shiroro hydro-power plant to evaluate the performance of a hydro-power plant based on the generation data of the plant and to suggest ways to improve the existing performance of the plant, in order to increase the reliability and availability of the plant and enhance full utilization of its potential.

III. METHODOLOGY

The materials used in this study include generation data of Shiroro Hydro-power station from Nation Control Center (NCC) of Transmission Company of Nigeria, design specification data ofShiroro Hydro-power Station, catalogue of the Francis turbines used and Matlab program. Similarly, quantitative tests were performed on the plant site to ascertain if all parts, systems, and auxiliaries were performing in accordance with design parameters. The method implemented in this study includes the following.

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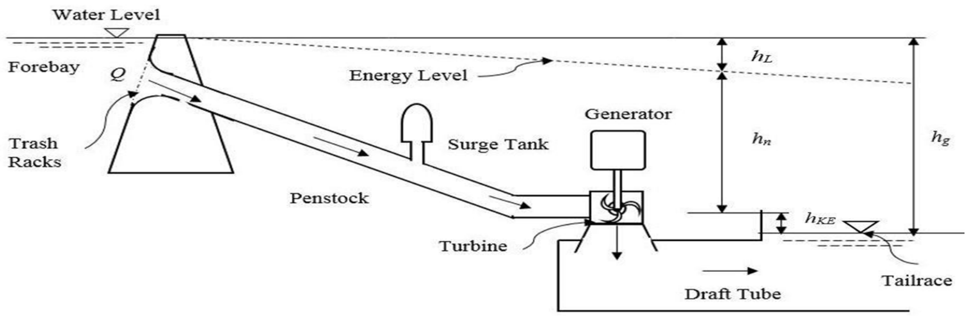

Figure 1: Schematic of a Hydro-Power Generation Plant

A. *Hydro-Power Plant Efficiencies*

In order to determine the hydro-power plant efficiencies, the following parameters were analyzed from the data obtained from the plant logbook.

1) *Net Head*

The net head (h_n) is the amount of head that is available for useful work at the turbine's inlet. Depending on the length of the penstock, the water flow rate and the velocity, head losses in the penstock could range from 5 to 10% of the gross head.

$$h_n = h_g - (0.1 \times h_g) \quad (1)$$

where h_g is the vertical distance between the water surface level at the intake and the hydro-power house (gross head (m)).

2) *Hydraulic Power of the Plant*

Waterfalls are used to generate hydropower. A hydropower plant's fuel is stream flow, and without it, generation stops. The hydraulic power (P_ψ) generated by the flowing water is expressed in kilowatt (kW) and is given as (Singh, 2009).

$$P_\psi = \rho g Q h_n \quad (2)$$

where ρ = water density (1000 kg/m^3)
g = acceleration due to gravity [m/s^2]
Q = flow rate of falling water [m^3/s].

3) *Shaft Power of Turbine*

The water strikes the runner blades radially and exits axially through a draft tube in a Francis turbine with a radial flow runner. The shaft power developed by the turbine runner that takes in flowing water at the rotor's outer perimeter in a radially inward direction and discharges it axially parallel to the rotor's axis in which the whirl component of the jet velocity at the exit is zero can be determined as:

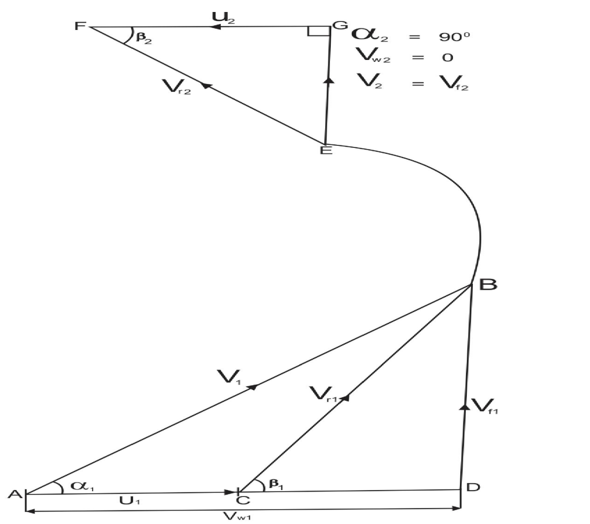

Figure 2: Velocity Triangle of a Francis Turbine

V_1, V_2 = Velocity of jet at inlet and outlet
U_1, U_2 = Velocity of blade at inlet and outlet
V_{w1}, V_{w2} = whirl component of jet velocity at inlet and outlet
V_{f1}, V_{f2} = Axial component of jet velocity at inlet and outlet
V_{r1}, V_{r2} = Relative component of jet velocity at inlet and outlet
α_1, α_2 = Design flow angle at inlet and outlet (guide vane angle)
β_1, β_2 = Blade angle at inlet and outlet.

From the velocity diagram, $P_s = \rho Q(V_{w1}U_1 \pm V_{w2}U_2)$ (3)

From the outlet velocity triangle, water flows out without whirl velocity ($V_{w2} = 0$)

$$P_s = \rho Q V_{w1} U_1 \quad (4)$$

$$U_1 = Cu\sqrt{2gh_n} \quad (5)$$

$$V_{w1} = \frac{V_{f1}}{tan\alpha_1} \quad (6)$$

$$V_{f1} = Cv\sqrt{2gh_n} \quad (7)$$

where Cu = Design speed ratio of the turbine
Cv = Design flow ratio of the turbine

4) Theoretical Power Generation

The electrical power that can be theoretically generated to the grid from the hydro-power plant generators is obtained from the conversion of the mechanical shaft power of the turbine into electrical power **as:**

$$P_{theoritcal} = \eta_g \times P_s \quad (8)$$

where η_g = design generator efficiency

5) Plant Efficiency

The efficiency of the plant taking into considerations the actual power generated from the given flow rate and net head, and the theoretical power that is developed for the same flow rate and net head is given as:

$$\eta_p = \frac{P_{gen}}{P_{theoretical}} \times 100\% \quad (9)$$

where P_{gen} = actual power generated by the hydro-power plant generators as obtained from the plant logbook.

6) Overall Plant Efficiency

The overall efficiency of the hydro-power plant is a measure of how efficient the hydraulic energy of the falling water is converted to mechanical energy by the turbines and to electrical energy by the generators. It is the proportion of actual electrical power generated by water generators to hydraulic power generated by falling water.

The hydro-power plant overall efficiency (η_o) is given as:

$$\eta_o = \frac{P_{gen}}{P_{\psi}} \quad (10)$$

B. Performance Parameter Indices of the Plant

In order to determine the hydro-power plant performance indices, the following parameters were analyzed from the data obtained from the plant logbook.

1) Capacity Factor

Capacity factor is the ratio of the plant's average energy output during a certain time period to its capacity. The factor of plant capacity (CF) is given as (Gbadamosi *et al.,* 2015)

$$CF = \frac{E_g}{I_c \times T} \times 100\% \quad (11)$$

where $E_g = P_{gen} \times T$ (total energy generated in MWh)
I_c = Installed capacity of the plant (MW)
T = running hour of the plant (hr).

2) Utilization Factor

The utilization factor shows how well the plant is handled in terms of downtime. It measures how well the plant's overall installed capacity is being utilized. It is the ratio of a plant's installed capacity to its maximum power generated during a given time period (s). If there is less water (both in flow and consequently in storage) than predicted, actual output may be lower than potential output and this greatly limits the utilization of the hydro-power plant.

The plant utilization factor (UF) is given as (Isaac *et al*., 2011)

$$UF = \frac{P_{max}}{I_c} \quad (12)$$

where P_{max} = maximum power generated (MW).

C. Development of Matlab Algorithm for Analysis of Plant Efficiencies and other Performance Indices

A MATLAB program was written that collects data from Microsoft Excel files that contain flow rate readings, gross operating head and actual power generated. Certain constants such as acceleration due to gravity, water density and plant design specifications were directly inputted to the MATLAB program. The program used these data mentioned and various thermo-fluid energy equations to calculate key plant parameters.

D. Data Source

The design specifications of some of the Shiroro hydro-power plant parameters are shown in Table 1. The daily total of mean discharge flow rates (Q), electrical power generated by the water generators (P_{gen}) and the gross operating head (h_g) data for the year 2019 - 2020 used for this study were collected from NCC for Shiroro hydro-power station. The maximum power generated for each month and the average of the daily data for each month were computed shown in Tables 2 and 3, for 2019 and 2020, respectively.

Table 1: Design Specifications of Shiroro Hydro-Power Station

Description	Value
Dam Height	115m
Crest length of dam	700m
Crest width of dam	7.5m
Base width of dam	300m
Main reservoir volume at full reservoir level (FRL)	7billion m^3
Maximum headrace level	382.50m
Maximum tailrace level	274.72m
Min. level below which no generation	355m
Spillway gates	15m x 16.65m
Penstocks	4 steel line, 6.30m diameter, 1400m length
Draft tube	Elbow tube, circular cross-section at inlet, 10.28m diameter
Turbine type	4 vertical Francis reaction turbines
Model	MB9 _055/1-4
Flow rate	181.3m^3/s
Net head	97m
Speed ratio (Cu)	0.86
Flow ratio (Cv)	0.28
Guide vane angle	27^0
Installed Capacity	600MW (4 x 150MW)
Unit Speed	150rpm
Generator efficiency	0.9

Source: Shiroro Hydro-Electric Power Station (2021)

Table 2: Monthly Average of the Generation data of Shiroro hydro-Power Plant (2019)

Months	Gross Operating head (m)	Flow Rate (m^3/s)	Power Generated (MW)	Maximum Power Generated(MW)
January	107.62	133.10	240.868	381.92
February	103.39	124.41	206.463	391.8
March	101.29	152.92	288.470	401.71
April	96.36	153.89	239.236	347.77
May	91.68	123.44	154.408	309.19
June	97.76	126.97	162.422	255.08
July	96.17	154.26	253.113	406.53
August	102.92	132.83	335.203	479.72
September	112.61	143.31	400.687	474.37
October	111.94	139.26	383.829	431.54
November	113.36	135.58	392.378	441.55
December	111.84	137.08	395.308	438.13
Average	103.91	138.09	287.699	396.61

Table 3: Monthly Average of the Generation data of Shiroro hydro-power plant (2020)

Months	Gross Operating head (m)	Flow Rate (m^3/s)	Power Generated (MW)	Maximum Power Generated(MW)
January	108.82	144.49	271.020	360.88
February	105.56	164.73	298.883	373.29
March	101.56	131.54	347.936	433.38
April	95.86	148.55	238.153	379.79
May	100.47	130.28	166.883	281.17
June	92.13	117.44	135.891	176.29
July	97.43	150.63	242.866	343.21
August	113.84	133.19	374.294	440.08
September	112.62	139.98	402.915	428.13
October	112.96	129.89	374.883	426.50
November	112.69	129.89	374.358	431.92
December	110.34	176.97	331.304	428.67
Average	105.36	141.47	296.616	375.28

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IV. RESULTS AND DISCUSSION

The performance parameter indices that were used in evaluating the Shiroro hydro-power plant and compared with international standard organization (ISO) best practices are discussed as follows:

A. *Plant Efficiency*

The plant efficiency curves for the reviewed period are presented in Figure 3.

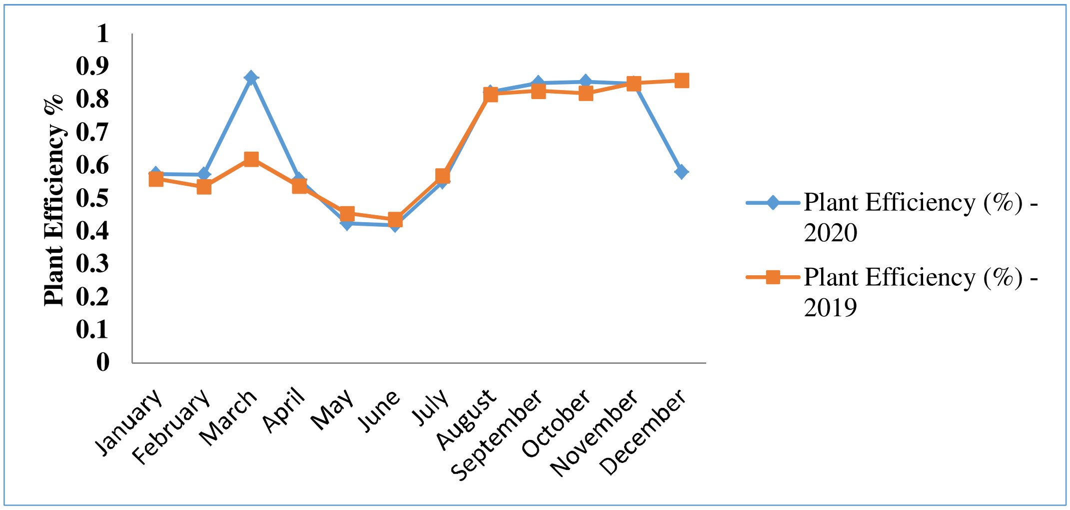

Figure 3: Monthly Plant Efficiency Curve of Shiroro Hydro-Power Plant

The plant efficiency of the hydro-power plant is an indication of the percentage of electrical power generated in comparison to the possible theoretical power that could have been generated from the obtained flow rates and net head if the four units of the plant were effectively harnessed without constraints of faulty units, poor water management as a result of low water head and low load demand from the grid, as regulated by NCC.

The average plant efficiency for 2019 is 65.65% with a minimum value of 43.56% in the month of June and a maximum value of 85.83% in the month of December, while the average plant efficiency for 2020 is 65.99% with a minimum value of 41.81% in the month of June and a maximum value of 86.66% in the month of March. The plant efficiency averages of 65.65% and 65.99% for the period under review shows that 34.35% and 34.01% respectively, of possible electrical power that could have been generated was loss due to equipment breakdown, poor water management and low load demand from the national grid.

B. *Overall Plant Efficiency*

The overall efficiency curves for the reviewed period are presented in Figure 4.

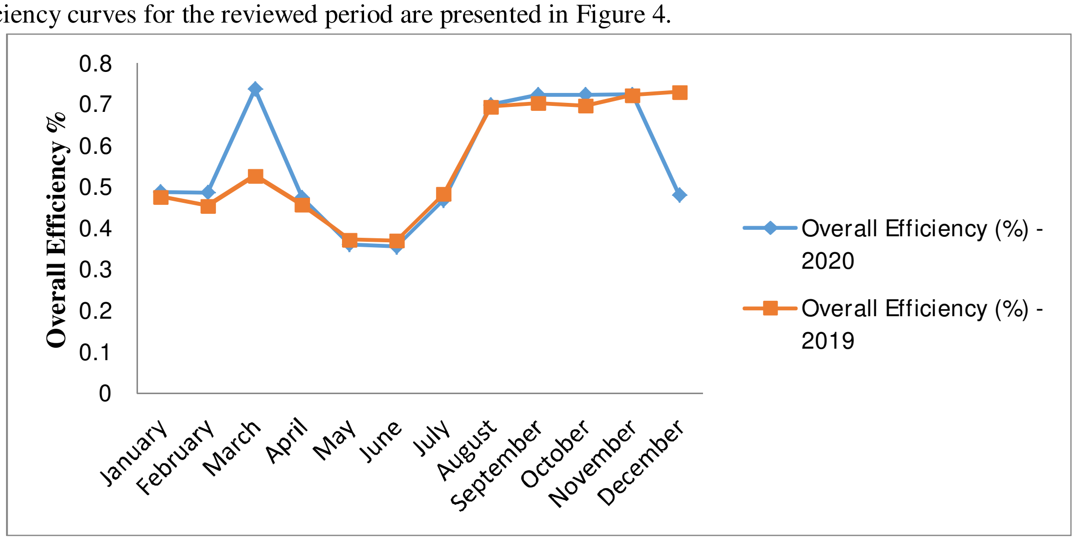

Figure 4: Monthly Overall Efficiency Curve of Shiroro Hydro-Power Plant

The overall efficiency of the hydro-power plant is an indication of how effectively the hydraulic energy of the falling water is converted to mechanical (and electrical) energy by the water turbine (and generator), respectively. The water turbine transforms hydraulic energy to mechanical energy, which is then converted to electricity by the generator.

The average overall efficiency of the plant for 2019 is 55.74% with a minimum value of 37.05% in the month of June and a maximum value of 73.01% in the month of December, while the average overall efficiency of the plant for 2020 is 56.02% with a minimum value of 35.56% in the month of June and a maximum value of 73.75% in the month of March. The low efficiency in June, 2020 indicates that 35.56% of the potential energy is converted to electricity and 64.44% of the energy is lost. The loss in energy is the combined effect of low effective water head and low discharge water flow rate from the lake. Because of uncertain climatic conditions, water spillage due to floods, inadequate maintenance, and inefficient maintenance procedures, the rate of discharge and the effective water head adversely affect plant operation.

The average overall efficiency 55.74% and 56.02% of the power plant for the period under review is below the expected minimum value of 80% required for optimum generation. This indicates a shortfall of 23.98% and 24.26% and more of hydraulic energy conversion respectively. A higher overall efficiency is desired to effectively harness the generated hydraulic power of the falling water. It was observed that the higher the generated MW in comparison to the hydraulic power, the more efficient the plant becomes.

C. Capacity Factor

The plant capacity factor curves for the reviewed period are presented in Figure 5.

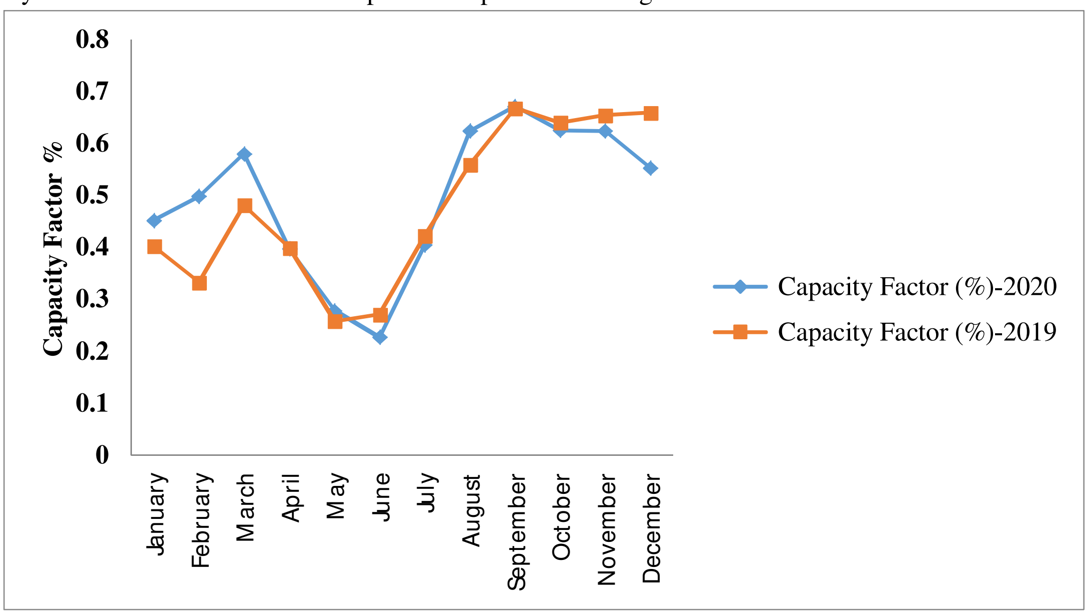

Figure 5: Monthly Capacity Factor Curve of Shiroro Hydro-Power Plant

The average capacity factor of the plant for 2019 is 47.85% with a minimum value of 25.74% in the month of May and a maximum value of 66.78% in the month of September, while the average capacity factor of the plant for 2020 is 49.44% with a minimum value of 22.65% in the month of June and a maximum value of 67.15% in the month of September as against standard practice of 50% to 80%. The capacity factor determines the characteristic behavior of the generating station. High capacity factor is required for a viable economic operation of the plant. The low capacity factor 22.65% and 25.74% of the plant for the period under review shows that the average energy generation of the plant is low in the respective months. This is due to force outage of two generating units on fault and low headwater elevation while the other units generated on reduced capacity due to poor water management. For the entire year of 2020 the generating unit 411G4 was out on fault and this also impacted the maximum capacity factor that could have been achieved during peak period generation. Low load demand from distribution companies is also another factor that limited generation by the hydro-power plant.

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In general, low average capacity factor 47.45% and 49.44% for the reviewed period signifies that the average energy generation is low as a result of excessive plant downtime. If scheduled routine maintenance of the plant and the average head of water is significantly improved, the frequency of failures and unavailability of the plant generating units would reduce and a high capacity factor will be achieved.

D. Utilization Factor

The plant utilization factor curves for the reviewed period are presented in Figure 6.

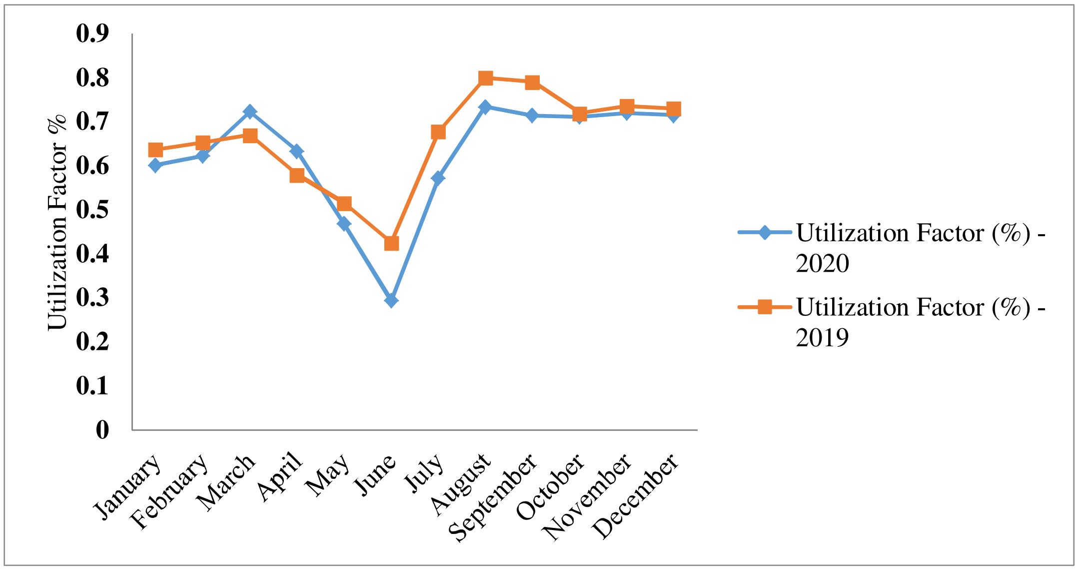

Figure 6: Monthly Utilization Factor Curve of Shiroro Hydro-Power Plant

The average utilization factor for 2019 is 66.1% with a minimum value of 42.51% in the month of June and a maximum value of 79.95% in the month of August, while the average utilization factor of the plant for 2020 is 62.44% with a minimum value of 29.38% in the month of June and a maximum value of 73.35% in the month of August. The plant's utilization factors are far below standard best practices of over 95%. The utilization factor trend illustrates how well the hydro-power station is managed in terms of downtime. The results demonstrate that the producing units were used less than their expected operating hours in a year. This is due to a lack of normal maintenance, poor water management, and the incidents of equipment fault. In order to reduce downtime and hence maximize utilization, hydro-power plant stations should maintain planned and routine predictive maintenance.

V. CONCLUSION

This study has developed an effective approach of evaluating the performance of Shiroro hydro – power plant on monthly basis with emphasis on the operational parameters such as plant efficiency, overall efficiency, capacity factor and utilization factor. The calculated plant efficiency shows an average of 65.65% in 2019 and 65.99% in 2020 which indicates that 34.55% and 34.01% respectively of the possible electrical power that could have been generated was lost due to equipment failure and poor water management. The overall efficiencies determined show an average of 55.74% for 2019 and 56.02% for 2020 as against international best practice of 80% and above. The capacity factor calculated shows an average of 47.85% for 2019 and 49.44% for 2020 as against standard practice of 50% to 80%. The utilization factor determined shows an average of 66.1% for 2019 and 62.46% for 2020 as against international best practice of 95%. Based on the averages of the performance indices evaluated and compared with the standard values, it can be concluded that the plant is utilized below the rated capacity in the period under review.

It is therefore recommended that the Nigerian government adopts this study as a framework for performance evaluation of hydro-power plants. This application will greatly improve the generation in the country which has been stalling as a result of plants generating below rated capacity. Professional training for technical employees and management is necessary to ensure personnel technical efficiency. Future research work in the line of this study can look into other renewal energy generating plants. Also other performance parameters not discussed in this study can be inoculated into future works.

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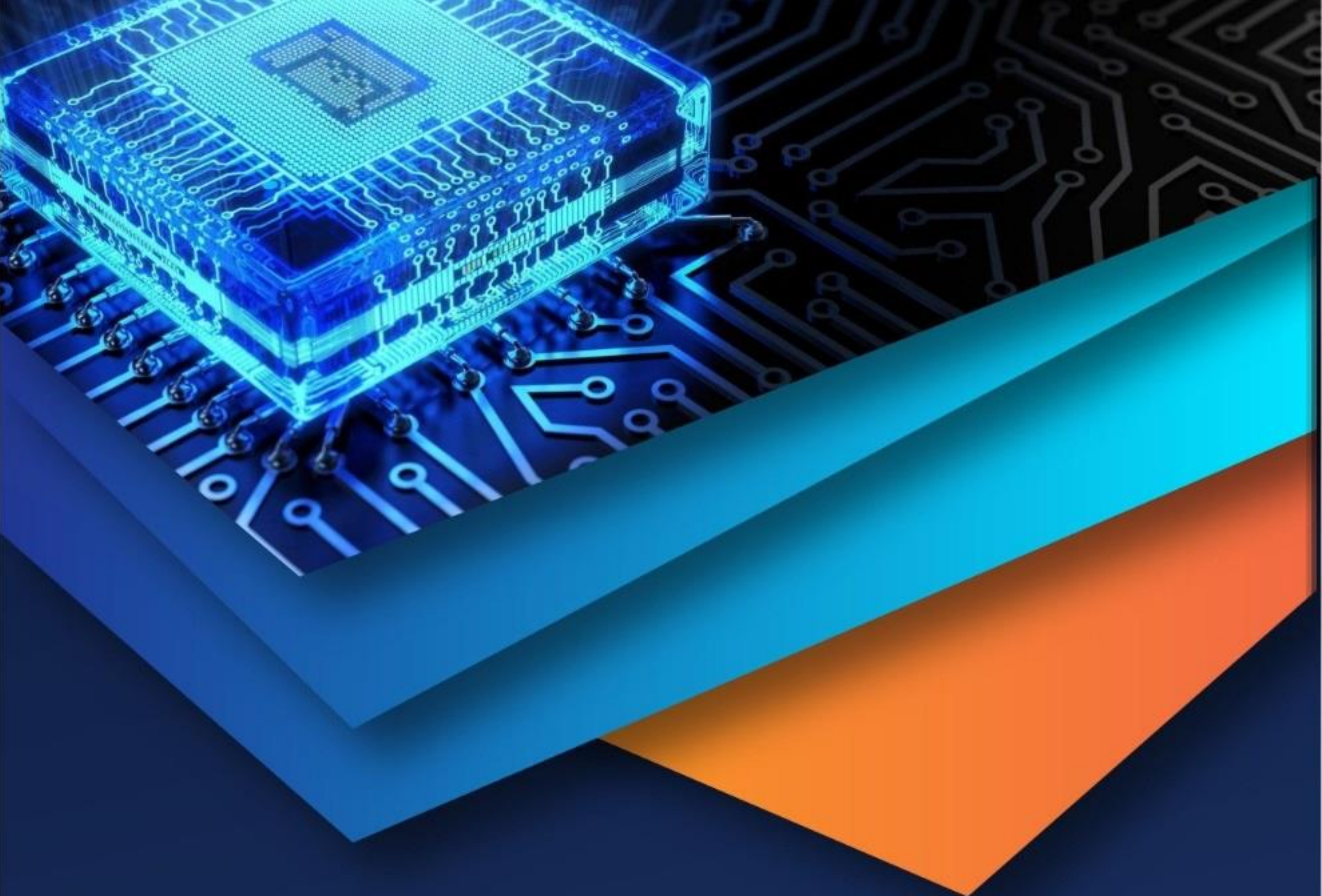

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