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Application of Response Surface Methodology (RSM) for the optimization of energy generation from Jebba hydro-power plant, Nigeria

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ABSTRACT

This research was performed to optimize the performance characteristics of the Nigerian Jebba Hydropower Plant in order to enhance its generation of electricity. Pertinent hydropower data were hourly collected from the plant from 8:00 am to 5:00 pm between 2016 and 2018. The coefficient of determination obtained from the response surface methodology (RSM) showed that discharge, pressure drop, stator temperature and water pressure strongly influenced the generation of estimated power. Also, the contour and surface plots suggested that the discharge (D) 8200.00–8600.00 m³/s and pressure drop (Pd) ranging from 27.50–28.50 m gave the optimal power generation indicating that both factors must be kept high when the hydropower plant is in operation. The instability of power generation was attributed to the reduction in the net available head as turbine inlet decreased. The study, therefore, showed that net power output, speed of the turbine, and efficiency of the hydropower plant could be optimized with increase discharge and gross head. Predicted optimal values for discharge, pressure drop, stator temperature, and water pressure were 8783.3667 m³, 28.59 m, 58.00°C, and 31.00 N/m² respectively.

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KEYWORDS

Jebba hydropower plant; optimization; RSM; power output; Nigeria

1. Introduction

Outside the issues of inadequate access to potable water and increase in environmental degradation, another major challenge of excessive population increase in developing nations is inadequate power supply for industrial and domestic uses (Owamah et al. 2013, 2017). Energy is not only essential for development; it is a powerful engine of social and economic opportunities (Owamah 2020a; Owamah et al. 2020). No country develops considerably without providing the minimum power required for sustainable economy. Previous studies have shown that the economic growth of any country depends to a large extent, on its energy output (Owamah and Izinyon 2015; Izadyar et al. 2016). Electricity generation and access in Nigeria are still abysmally low even as the country is the largest in Africa in terms of population (about 200 million) and economy (Owamah 2020b; Onokwai et al. 2019a; Balogun et al. 2019; Ladokun et al. 2018).

Presently, the capacity of electricity generation in Nigeria stands poorly at about 7,566.2 MW with 15.61% being obtained from renewable sources (Ogbonnava et al. 2019; Aliyu et al. 2018; Ozoegwu et al. 2017; Onokwai et al. 2019b). Though hydropower accounts for about 32% of the installed commercial electric power capacity in Nigeria, meeting the electricity demands of Nigerians remains a huge challenge (Onokwai et al. 2019c). The situation has further been worsened by the inability of the current power stations to operate at full capacities (Ogbonnava et al. 2019; Okonkwo et al. 2017). Assessing the different aspects of a hydropower system requires the use of multiple performance criteria for characterization of system alternatives. Jebba Hydropower Plant (JHP) has been performing below the design efficiency

as a result of hydrological issues such variability in the volume of water available for operating the turbines (Sule and Surajudeen 2017; Mythili et al. 2013; Olukanni et al. 2016). Notwithstanding these hydrological challenges, the JHP is expected to generate electricity at pre-determined level all through the year. Achieving this will surely require optimization of process parameters (Otti and Nwafor 2012). Though numerous techniques have been used to improve the efficiency of hydropower plants, choosing any of the techniques however depends on the hydropower and reservoir system features, data availability, set goals and imposed constraints (Bosona and Gebresenbet 2010). Some of the optimization techniques are Dynamic Programming (Otti and Nwafor 2012); Stochastic Programming (Mythili et al. 2013), Heuristic Programming, e.g. Genetic algorithms (Ghadami et al. 2009), Neural networks and others (Wei and Hsu 2008). While Rana and Patel (2018) investigated the determination of best location for small hydro power project using multi-criteria techniques, Ghimire and Reddy (2013) applied Swarm optimization to evaluating the optimal reservoir operation for hydropower generation. In spite of these, in relation to hydropower generation optimization, researchers are still aspiring to new and more effective optimization techniques given the issues of high dimensionality in the majority of existing models.

Furthermore, to the best of our knowledge, literature contains scanty or no information on the optimization of the performance characteristics of hydropower plants to enhance electricity generation using the Response Surface Methodology (RSM). This research was therefore focused

on using the RSM to optimize the performance characteristics of the Jebba hydropower plant in Nigeria being one of the most important hydropower stations in the country. The aim was to better understand the relationship between operating conditions and response (hydropower generation) and to establish the optimal conditions of the process using the RSM. The method is crucial for developing new processes, optimization of performance, improvement of design and formulation of new products (Myers and Montgomery 2000).

The RSM combines statistical and numerical optimization approaches to generate empirical equations and determine the impact of given conditions on targeted responses. It was originally developed for the optimization of industrial processes with many input factors. While the performance measures are known as response, the input variables are the independent conditions (Laougé et al. 2020). Onokwai et al. (2019b) applied the RSM to optimize the energy and exergy efficiency of parabolic dish cooker with results showing that solar irradiances and temperature had huge impact on efficiency.

2. Methodology

2.1. Brief description of Jebba hydropower plant

Jebba hydropower plant (JHP) located downstream of Kainji Dam along the River Niger, Nigeria, was commissioned in 1983. It has a lake capacity of approximately 25% the size of Kainji reservoir. JHP consists of a spillway and powerhouse having water inlet. The powerhouse is made up of six turbines, each having a capacity of 96.4 MW and a total installed capacity of 578.4 MW at a rated net head of 27.6 m and discharge of 385 m³/s (Sule and Surajudeen 2017). It should be noted that the maximum output of each turbine (generating unit) is 102.9 MW at a maximum net head of 29.3 m as shown in Figure 1. Tables 1–3 respectively show the operating conditions for the plant, turbine and generator (Sule and Surajudeen 2017).

2.2. Collection of data

Relevant hydropower generation data such as discharge, pressure drop, water velocity, field current, operating head, turbine speed, temperatures (at the stator winding, turbine bearing, sump tank, stator core, pilot, Gov. oil, sump, thrust bearing, turbine bearing, generator guide bearing), vibration level voltage, power, air pressure (at the supplied

compressor, generator brake, pressure tank), operating guide valve, and oil pressure (at the Gov. oil and pilot supply) recorded on hourly basis from 8:00 am to 5:00 pm for three years (2016, 2017 and 2018) were obtained from the Management of Jebba hydropower plant.

2.3. Mechanical power and hydraulic turbine efficiency computation

The mechanical power and hydraulic turbine efficiency were calculated using Eqns. (1)–(4) according to Wenjing (2017):

$$P_m = \eta \cdot \rho \cdot g \cdot H_{net} \cdot Q_{dis} \quad (1)$$

$$Q_{dis} = k_g \cdot OP \cdot \sqrt{2 \cdot g \cdot H_{net}} \quad (2)$$

$$H_{net} = H_{p_out} - H_{s2} \quad (3)$$

where

$$OP = G \cdot A_p \quad (4)$$

where, P_m is the mechanical power and η is the efficiency of the turbine.

While H_{net} is the net head i.e difference between the penstock water head outlet (H_{p_out}) and the head of downstream surge (H_{s2}), OP is the effective gate opening which is the area of water entering the gate via a discharge flow (Q_{dis}) under gravity (g). G is the percentage of gate opening. The gate opening, G was simulated using the linear function with respect to time whereby the gate moves 1% of full opening every second (Wenjing 2017). Equations of the different forms of head loss as documented in Wenjing (2017) were carefully adopted and utilized for head loss computations.

2.4. Response Surface Methodology (RSM)

The experimental work was considered and chosen from the design database of the software used before the application of the RSM. Second-order response surface methodology was utilized in the research as shown in Eqn. (5) to obtain the main interaction factors (independent variables) such as discharge, pressure drop, water and oil pressure, and stator temperature, etc. and how they affect the efficiency and performance of the hydropower plant.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \sum_{j>1}^k \beta_{ij} x_i x_j \quad (5) \quad (\text{Laougé et al. 2020; Hossain et al. 2017; Montgomery et al. 2001});$$

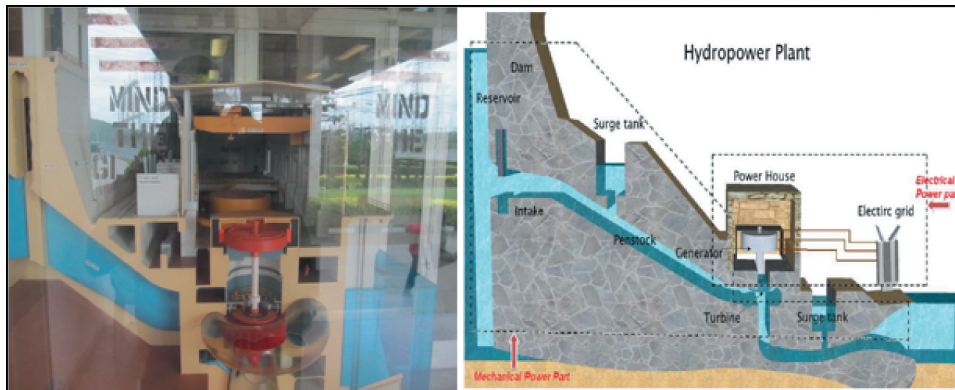


Figure 1. Jebba hydropower plant and its components (Sule and Surajudeen 2017).

Table 1. Operating conditions for the plant.

Plant	Parameters
Number of units	6
Total rated output	578.4 MW
Length of power wheel	206 m
Width of power wheel	36 m
Max. capacity of crane	450 Tonnes
Number of intake gates	6
Height of each intake gate	12.4 m
Width of intake gates	10 m
Inside diameter of each steel penstock	10 m

Table 2. Operating conditions for the turbine (Fixed blade).

Plant	Parameters
Net head-rated	27.6 m
Net head-maximum	29.3 m
Output at rated net head	96,400 kW
Output at maximum net head	102,900 kW
Speed	93.75 rpm

Table 3. Operating conditions for the generator (vertical shaft synchronous).

Plant	Parameters
Base load rating	103,500 kW
Continuous maximum rating	119,000 kVA
Voltage	16 kVA
Power factor	0.85

where, x_1 and x_2 are coded independent variables such as discharge (D) and pressure drop (Pd)

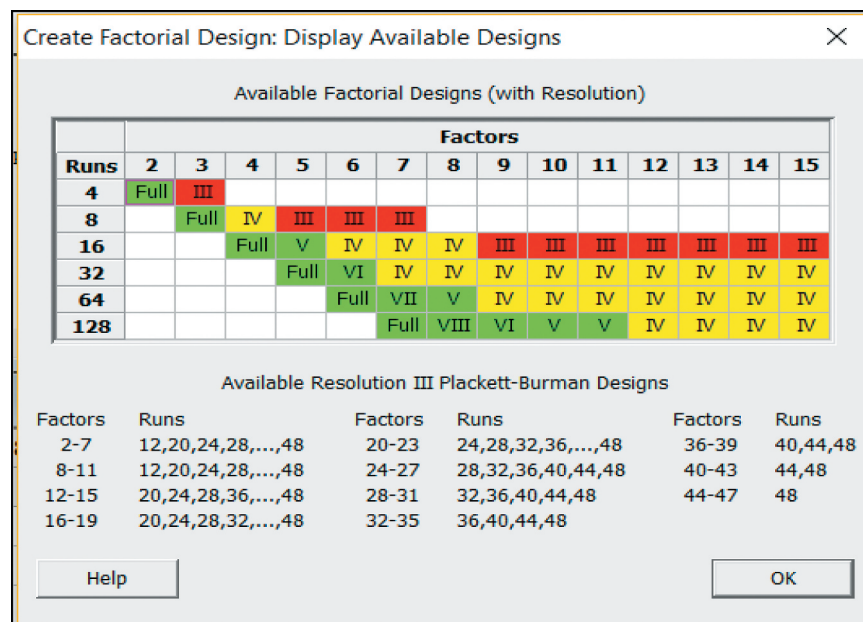
y is estimated power known as dependent variable (response). While β_0 is the constant coefficient, β_i , β_{ij} and β_{ijk} are the coefficients for linear, quadratic and interaction effects, k is the number of factors, ϵ_i is the random error in the experiment. The coefficient of determination R^2 indicates the quality of the polynomial. Performance of the model was ascertained by analyzing its results with ANOVA. The experiments were done using predefined independent variables such as discharge, pressure drop, water and oil pressure, stator temperature, etc. These variables were selected due to their influences on electricity generation from hydropower plants (Sule and Surajudeen 2017). The Design Expert

® (trial version 8.7.0.1, Stat Ease, USA) software was used for the design and statistical analysis of the hydropower generation process parameters.

2.5. Process optimization using the RSM

The process data comprising the output power and other operating factors for enhancement of efficiency were collected with the permission of the Management of Jebba hydropower plant in order to create an optimized model for power generation by the pressure head and discharge in the face of constraints like the temperature of the turbine, oil pressure for lubrication and cooling of the bearings as well as the air pressure. These constraints were meant to be reduced to maximize power output from the plant. As shown in Figure 2, the design from the software shows options for the application of 2-level factorial approach with different experimental runs. In this case, there were 35 experimental runs ranging from 2016 to 2018. For experimental runs between 32–64, 6 factors were accommodated. The RSM was conducted in two stages. First, the consideration of discharge taken as 'D' and pressure drop between the head and tailwater taken as 'Pd' of which an empirical model and its optimization for maximum power output were analyzed. The second stage involved the development of a more laborious model consisting of the operating conditions while constraining D and Pd to see the effect of the operating conditions on maximum power generation. The other factors considered were the stator temperature ' T_{st} ', the water pressure meant for cooling the generator ' P_{water} ' and the oil pressure ' P_{oil} ' meant for cooling and lubrication of the bearings. The factors chosen were done on the basis that the parameters showed changes during the operation of the plant. Other parameters that showed relative consistency in their magnitude (values) were not considered for this modelling.

The complete factorial design was implemented using the exponential symbolisation 2^k , where k stands for the number of factors (independent variables) to be used in the experiment.

**Figure 2.** A 2-Level factorial design.

3. Results and discussion

3.1. Three (3)-year monthly power generation

Figure 3 shows the monthly power generation for 2016, 2017 and 2018. There was no power generation in the month of July 2017 due to mechanical failure caused by a rapid drop in pressure from the head and tailwater. Also, the instability in power generation was as a result of various operating parameters of the turbine such as stator temperature, water pressure, discharge, oil pressure and vibration level, etc. (Adeniyi et al. 2018; Kougiassa et al. 2019). The average estimated power recorded for the three years was about 3000 MW.

3.2. First RSM for discharge and pressure drop analysis

For the 'D' and 'Pd', maximum and minimum values were collected without coding at 5% significant level as shown in Figure 4.

The first and second response surface methodology respectively yielded Eqns. (6) and (7).

$$EP_w = -7421 + 2.169 D + 36.6 Pd - 0.000126 D*D(6)$$

$$EP_w = 5173 + 1.58 D + 1636 Pd - 1092 T_{st} - 1033 P_{water} + 884 P_{oil} - 0.000130 D*D - 42.7 Pd*Pd + 3.8 T_{st}*T_{st} - 1.3 P_{water}*P_{water} - 9.76 P_{oil}*P_{oil} - 0.136 D*Pd + 0.0742 D*T_{st} + 0.0106 D*P_{air} - 0.0064 D*P_{oil} - 2.3 Pd*T_{st} + 31.6 Pd*P_{water} + 28.7 Pd*P_{oil} + 12.9 T_{st}*P_{water} - 8.1 T_{st}*P_{oil} - 16.1 P_{water}*P_{oil} (7)$$

In these, several factors such as stator temperature, D, Pd, P_{oil} and water temperature were considered. The analysis of variance (ANOVA) conducted showed that factors D and Pd contributed well to the production of EP_w as indicated by the *p*-value. The interaction factors showed that Pd*Pd did not fit the data. In a way of making a regression model in which the RSM would be based on more accuracy, the Pd² interaction factor was truncated from the model to be generated as well as D*Pd factor. The coefficient of determination (R²) from the model was 53.96% showing that the relationship among the factors was not a perfect one and that there were other factors that influenced the production of EP_w. The second RSM was then conducted by truncating the effect of Pd² interaction factor and D*Pd. After the 2nd RSM analysis,

the *p*-values of all the variables were less than 0.05. The regression model from the RSM revealed that power generation was strongly affected by discharge as shown in Figure 6.

3.3. Contour and surface plot for the RSM

The contour and surface plots suggest that the discharge from 8200.00–8600.00 m³/s gave the best power maximization as shown in Figures 5 and 6. The maximum power was attained with a combination of pressure drop ranging from 27.50–28.50 m. Hence, for maximum production of power, factors (D and Pd) must be kept high. The sudden drop in power generated as shown in Figure 5 could be attributed to mechanical failure caused by continuous pressure drop from the head and tail water (Kuriqi et al. 2019).

3.4. Response optimizer for EP_w

In the response optimization to determine the values of the factors required for optimal production of power, none of the factors was constrained or held at any point. The RSM produced the minimum, maximum and optimal generation of EP_w by finding every possible way of combining the discharge and the pressure drop in the regression model of Figure 7. As shown in Figure 8, at maximum discharge, maximum EP_w was found to be reduced. Having achieved this, the process was iterated to observe the effect of operating conditions for the generation of a complex model. The variations in pressure drop (Pd) and discharge (D) as recorded in Figure 8 was as a result of irregular water inflow at the reservoir. This agrees well with the report of Olofintoye et al. (2016) and Feng et al. (2019) that irregular water inflow affects Pd and D in hydropower plants.

3.5. Second RSM for operating conditions analysis

3.5.1. Customization of RSM design

By defining the high and low values of the five different factors shown in Figure 9, the RSM was applied again for attainment of optimal result. This gave a much higher R² value of 77.8 signifying a good relationship among the parameters in the model. This was as a result of utilizing all the operating conditions while constraining D and Pd in order to

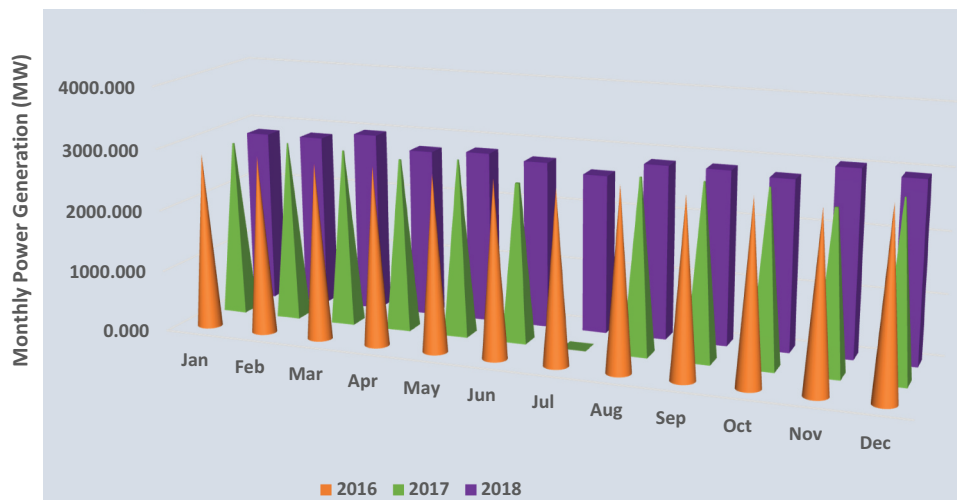


Figure 3. Monthly power generation of the Jebba hydropower plant from 2016–2018.

Define Custom Response Surface Design: Low/High

Low and High Values for Factors

Factor	Name	Low	High
A	D	7139.25000000	8783.36666666
B	Pd	26.1256666666	28.5866666666

Worksheet Data Are
☐ Coded
☒ Uncoded

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Figure 4. Custom response surface design.

be able to gauge the effect of the operating conditions on peak power generation. The truncation of variables were not

considered in the new model, in order to see the effect of all the factors and find out if there was a considerable increase in the expected power. Furthermore, the inclusion of the operating conditions might not necessarily add effects and significance in the p -value as they are factors for keeping the operation of the generator cool. Hence, the study examined the surface and contour plots and also performed a comprehensive ANOVA to execute a regression model for energy optimization as shown in Table 3. The fluctuation of power generated in Figure 10 was as a result of instability in the net available head at the turbine inlet as the velocity of water flow for a particular penstock increased (Ming et al. 2017; Ladokun et al. 2018).

3.5.2. Optimization plot

In the response optimization to determine the values of the factors required for optimal production of power, D and Pd were constrained so as to ascertain the condition of the previous optimization. The RSM produced the minimum,

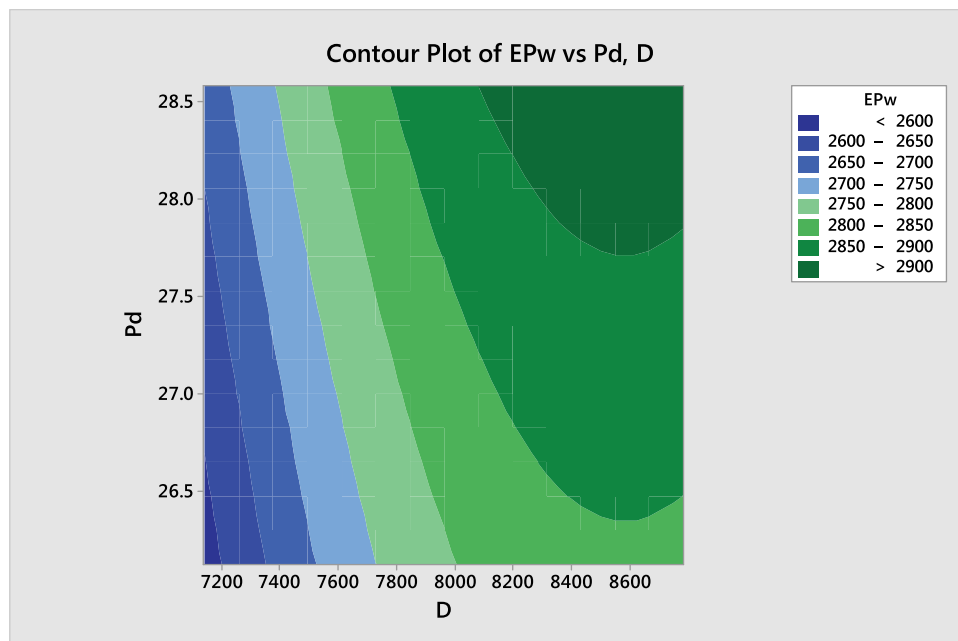


Figure 5. Contour plot for the production of EPw [D, Pd].

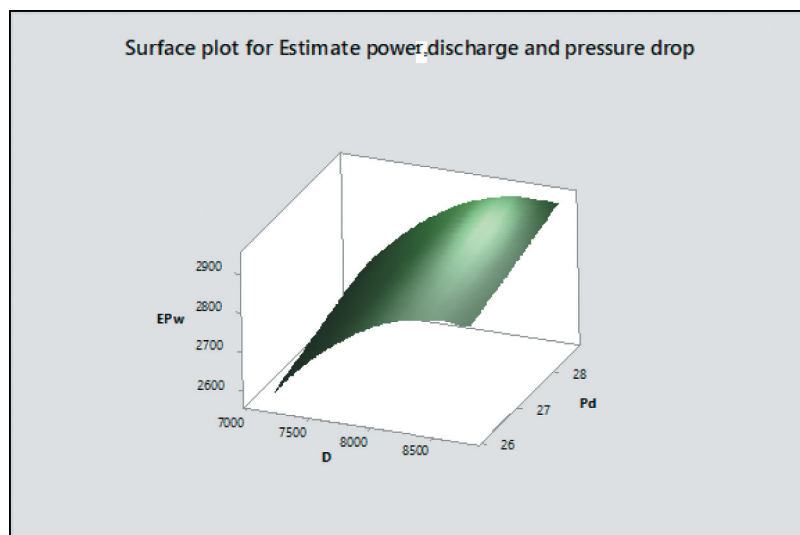


Figure 6. Surface plot for the production of EPw [D, Pd].

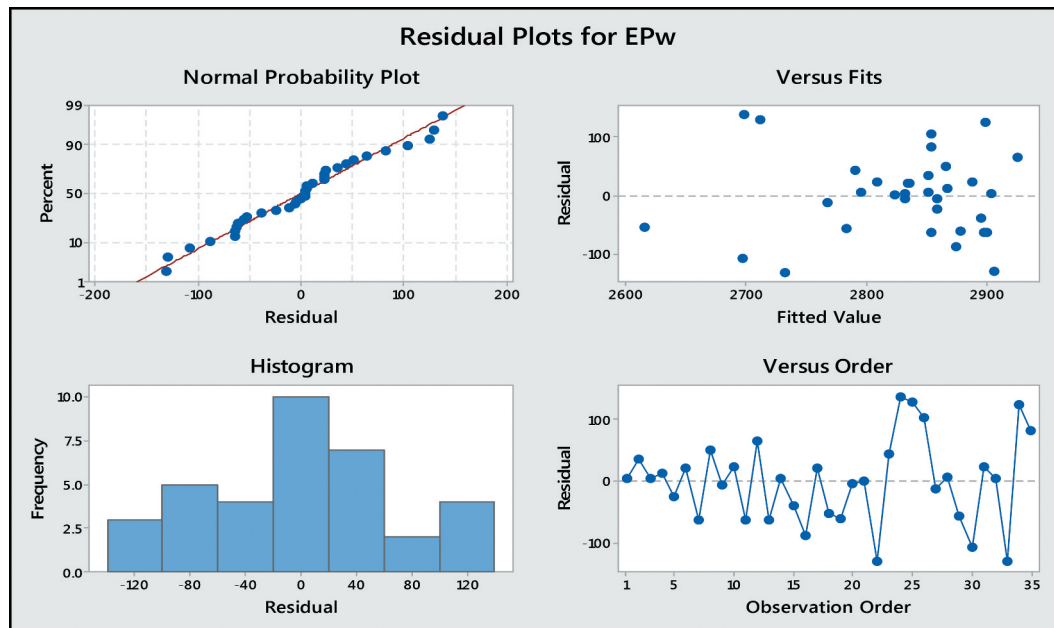


Figure 7. Residual plots for the discharge and pressure drop of EP_w.

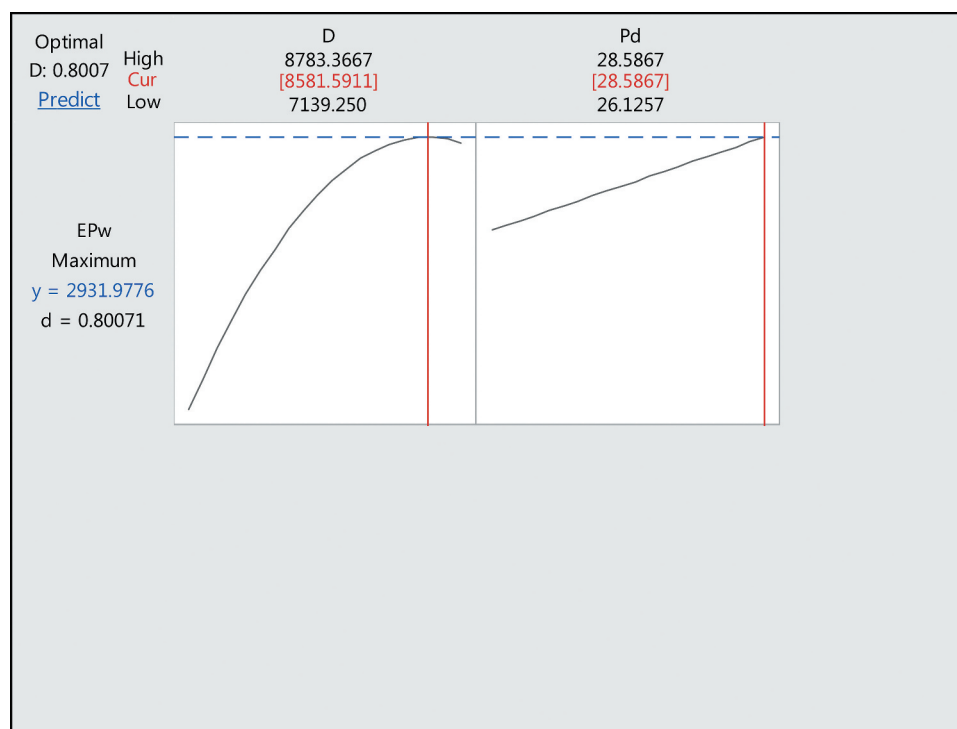


Figure 8. Optimization plot of the response surface model.

maximum and optimal generation for the production of the EP_w by combining all the factors in the regression model as shown in Figure 6. From Figures 11 and 12, the maximum value of the discharge reduced the maximum attainable EP_w. Figure 12 also shows a significant increase in the estimated power from 3128.25 to 3175.63 MW. It was deduced that a reduction in the net available head at turbine inlet led to instability in hydropower plant efficiency. Results obtained showed that varying the discharge, pressure drop (operating head), stator temperature, and water pressure had a huge effect on electricity generated, turbine speed and efficiency of the hydropower. This indicates that net power output, speed

of the turbine and efficiency of the hydropower plant could be optimized with increase in discharge and gross head.

Also, it was observed in Figure 12 that increase in discharge (D), stator temperature (T_{st}) and water pressure (P_{water}) led to increase in estimated power generated (EP_w) as the pressure drop (Pd) and oil pressure (P_{oil}) decreased (Sorachampa et al. 2020; Grigoriu et al. 2018). The optimized value of discharge ranged from 8200–8600 m³/s. It was further noted that the larger the discharge, the more energy was made available for conversion to electric power as shown in Figure 12. Also, from the hydrological data obtained from the Jebba hydropower plant, lower turbine discharge values

Define Custom Response Surface Design: Low/High

Low and High Values for Factors

Factor	Name	Low	High
A	D	7139.25000000	8783.36666666
B	Pd	26.1256666666	28.5866666666
C	Tst	53	58
D	P _{water}	29	33
E	Poil	31	37

Worksheet Data Are

☐ Coded

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Figure 9. High and low values for the five factors for the RSM.

rendered the turbine less efficient such that at very low reservoir levels, the turbine was shut down as a result of water management. This is as a result of the fact that Jebba hydropower plant operates via fixed turbine blades which cannot be adjusted to run at low reservoir level (Adeniyi et al., 2018). Achieving pressure drop (operating head) of about 28 m as shown in Figure 12 means a higher water pressure across the turbine runner which would lead to increase in power generation. It was deduced from the optimization that even a small increase in head makes a significant improvement in hydropower generation. This may be achieved by re-grading the tailrace to lower its level slightly in order to increase the overall head (Feng et al. 2020). It was also observed that thermal instability of generator windings occurred when the temperature fluctuated (Feng et al. 2020). Maintaining the windings temperature at 58°C or lower, would enable the generator run at its maximum capacity without risk of insulation failure. The hotter the windings temperature, the less load the generator would

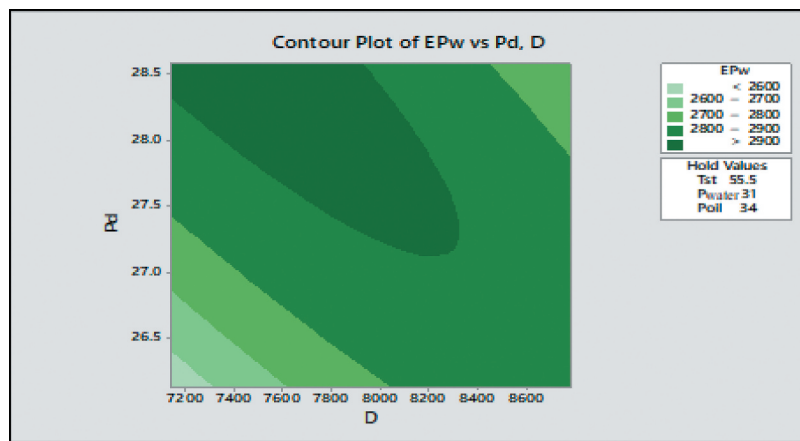


Figure 10. Contour plot for the production of EPw.

Response Optimizer: Options

Constraints

Variable	Constraint	Hold Value	Lower	Upper
D	Hold at value	8581.5911		
Pd	Hold at value	27.5867		
Tst	No constraints			
P _{water}	No constraints			
Poil	No constraints			

Starting Values

Variable	Starting Value
D	8581.5911
Pd	27.5867
Tst	
P _{water}	
Poil	

Confidence level for all intervals: 95

Type of confidence level: Two-sided

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Figure 11. Response optimizer for the five factors-1.

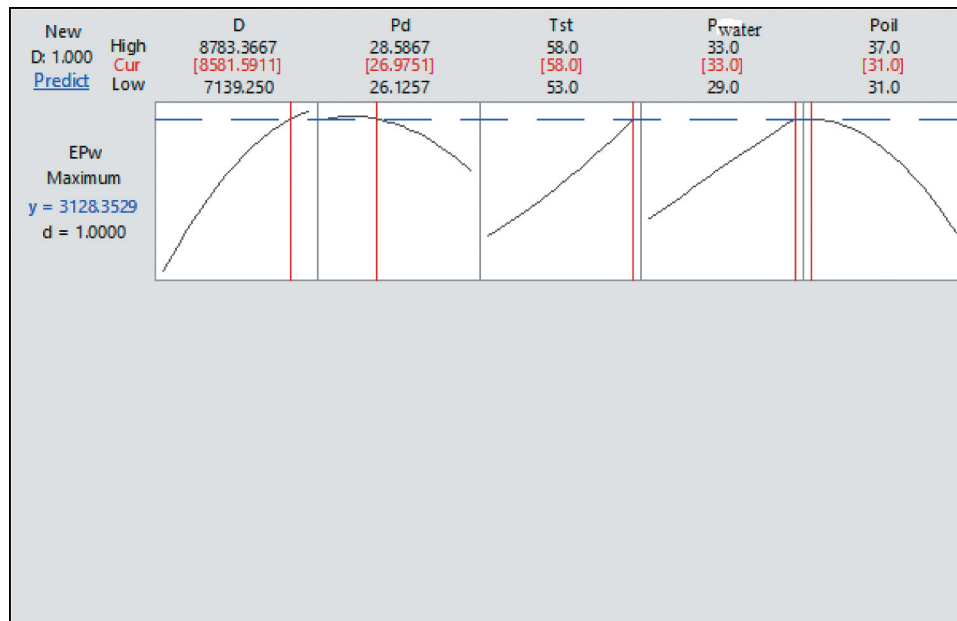


Figure 12. Response optimizer for the five factors.

sustain. Results obtained from the Maintenance section in Jebba hydropower plant showed that the turbine had tripped on many occasions on high temperature alarm thereby making the generator to undergo cooling using water flowing through radiators (16 in numbers) installed round each generator (Chiromo et al. 2016).

4. Conclusion

This study was aimed at optimizing the performance characteristics of Jebba hydropower plant, Nigeria using response surface methodology (RSM) to enhance the estimated power generated from the plant. Results obtained showed that electricity generated, turbine speed and efficiency of the hydropower plant were influenced by discharge, pressure drop (operating head), stator temperature, and water pressure. It also showed that the power output was optimized when the discharge and pressure drop were kept high as revealed by the contour and surface plots obtained with the RSM. Decreasing the net available head as turbine inlet reduced resulted in a variation of power generation. Also, the RSM simulation of the experimental data showed that the optimal values for discharge, pressure drop (operating head), stator temperature, and water pressure were 8783.37 m³, 28.59 m, 58.0°C, and 31.00 N/m² respectively.

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Authors contributions

A. O. Onokwai, H. I. Owamah, M. O. Ibiwoye, G. C. Ayuba and O. A. Olayemiconceived the theory, formulation and methodology. Onokwai, Ibiwoye, Ayuba and Olayemi sourced and analysed the data. Onokwai,

Owamah, Ibiwoye and Ayuba prepared and edited the manuscript. The results were discussed and commented on by all the authors. Onokwai and Owamah handled the submission and review processes.

Availability of data and materials

Extra data that support the findings of this study are available from the corresponding author [Onokwai, A. O.] upon reasonable request.

Disclosure statement

Authors declare that there is no competing interest whatsoever.

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