Open Access Library Journal
2022, Volume 9, e8476
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Optimal Speed Control and Regulation of Salient Pole Hydro Turbine Generators in Nigeria: Artificial Intelligence Approach

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How to cite this paper: Ngang, N.B. and Aneke, E.N. (2022) Optimal Speed Control and Regulation of Salient Pole Hydro Turbine Generators in Nigeria: Artificial Intelligence Approach. *Open Access Library Journal*, **9**: e8476.
https://doi.org/10.4236/oalib.1108476

Received: February 11, 2022
Accepted: March 19, 2022
Published: March 22, 2022

Abstract

This research is being carried out to improve the quality of power supply caused by voltage fluctuations due to unstable hydro turbine generator speeds. A solution based on Fuzzy Logic Control was created to eliminate the problem of epileptic power supply in some parts of Nigeria, which was caused by the slow rotation of the hydro turbines. This is accomplished by creating a membership function to analyze the causes of slow turbine rotation, a membership function to increase turbine rotation, a fuzzy rule to generate constant power supply when the turbine rotates fast, and a model for Hydropower Generator speed control using a fuzzy software tool. When fuzzy is added into the model, the outcome gained is a stable power supply, which occurred as a result of increased turbine speed rotation and increased water flow via the hydroelectric penstock. When a fuzzy controller is utilized, the outcome of the turbine's speed rotation is better than the proportional-integral (PI).

Subject Areas

Electrical/Electronic Engineering

Keywords

Optimal Speed, Control and Regulation, Salient Pole, Hydro Turbine Generators, Artificial Intelligence

1. Introduction

Hydropower facilities are built to create electrical or mechanical power in response to the energy demand of the surrounding area.

The generated frequency of a producing plant fluctuates due to variations in load; consumers' need for electricity causes a load of a hydroelectric generator to constantly shift. The use of current control theory in the design of hydro turbine speed control systems has grown in popularity. Remember that the hydro-turbine is responsible for maintaining the active power and rated frequency at rated speed; any change in load causes a deviation in the speed, which directly deviates the rated frequency and causes the generators to lose synchronism [1] [2]. Frequency variation is acceptable up to a point; however, if frequency deviates beyond acceptable limits, it may result in malfunctioning electrical equipment and appliances that are sensitive to frequency deviations. Frequency should remain constant for satisfactory power system operation, albeit this is not always the case. In Nigeria, we use a 50 Hz frequency; under peak load, you can get as low as 49.5 Hz, and during off-peak hours, you can get as high as 50.3 Hz.

The authors of the study [3] backed this up by stating that hydropower is a good option. When a sudden load shift occurs, an automatic speed governor is employed to control the turbine output. Closed-loop control was employed for supervisory control and data acquisition in that paper (SCADA). Because the complexity of modern power systems has increased, novel control strategies, such as Genetic Algorithm (GA)-based learning [4] [5], have been developed to address the problems given by new technologies. The turbine load of a hydropower station fluctuates as the generator load changes; a change in a load of a hydro turbine produces a change in its rotation speed, resulting in a discrepancy between its actual and rated speed. As a result, if a propeller turbine is suddenly emptied or has no load, its rotational speed increases significantly. The majority of power system models are non-linear, yet they are linearized for tuning traditional controllers. The ANN (Artificial Neural Network) is a well-known nonlinear system approximation that may approximate higher-order functions. Nonlinear systems can also be precisely controlled with ANN [6]. Previous work in this area had been done, but with less attention on dynamic modeling [7] and [8]; the Fuzzy Logic Controller is user-friendly and can meet the issues of hydro turbines (Frances type). When a turbine's load increases, its rotational speed falls below the rated speed. It's usually a good idea to apply a load that keeps the turbine and, by extension, the generator, operating within their rated speeds and not beyond their allowable strength. When the angular speed of a turbine or generator varies too much, the frequency or magnitude of the electric current (Ac) at 50 Hz or 60 Hz varies proportionally. [9] demonstrated that in a hydrothermal power plant, a precise signal is required to operate the gate, which must be detected and fit the demand of a rapid big shift in the loads. He also stated that the maximum rapid increase and drop in load system must be predicted, as well as the resulting manipulation in gate position. When a sudden load change occurs, a hydroelectric automatic speed governor is utilized to control the turbine output. This is to prevent the turbine and generator's rotation speeds from increasing to the point where the synchronizing toque coefficient is affected. Over voltages are seen in power plants for higher speeds and under voltages for lower speeds. The output of the micro-hydro turbine can be adjusted to match the change in external load by adjusting the water flow into the turbine. Artificial control methods do not meet this need due to the rapidity or rapidity of load changes in the generator. This is why most hydropower plants have an automatic mechanical "governor" to control the flow of water through the penstock to the turbine blades. However, the governor's intricate structure, combined with its high cost, makes it unsuitable for tiny hydroelectric power plants. Mini hydroelectric generators, on the other hand, use water flow control valves to regulate the rotational speed. Electronic load (ELC) and dump load are utilized once again to balance the excess power from the generator, providing current flow stability at a competitive price. Modern power system networks are operating under extremely stressful situations as a result of increased electricity power [10]. The author of the study [11] noted that the need for electric energy in modern life cannot be overstated; that the epileptic power supply to support the expanding population and economic expansion of developing countries is becoming an endemic concern. It would be preferable to devise a method of minimizing these issues at the generating station before they reach the transmission and distribution sectors. Other tools might readily be used to assess the economic and technical viability of a wide number of technological possibilities, as well as to account for fluctuations in technology costs and energy resource availability. The purpose of this research is to employ a Fuzzy Logic Controller to control the flow of water from the penstock to the turbine blades, ensuring that the generator and turbine run at the same speed. This accounts for abrupt load variations, which aren't taken into account by other approaches used in this type of research work.

1.1. Aim of the Study

The paper aimed at solving the endemic challenges posed by inadequate regulation of hydro turbine speed for good quality of power supply in a hydro power station using Artificial Intelligence software.

1.2. Objectives

As the demand for power is increasing daily, new technologies are being introduced into the electric power generation, transmission and distribution network. The objectives must be stated in behavioural terms to reflect the methodology as we can see later in section three; the specific objectives are to:

- Design a membership function that will analyze the causes of slow turbine rotation;
- Design a membership function that will increase the rotation of a turbine;
- Design a fuzzy rule that will generate constant power supply when the turbine rotates fast;
- Designing a model for Hydropower Generator speed control using fuzzy software tool;
- Compare Hydro turbine rotation speed without and with fuzzy versus time.

2. Materials and Methods

A hydroelectric power plant was employed in this design (HEPP). The basic layout of a hydroelectric power plant (HEPP) whose speed control must be managed to obtain the appropriate response is shown in **Figure 1**. A tunnel and penstock transport water from a reservoir to a turbine, where it is discharged into tail water. Except for solitary operation, a generating unit can be in one of three modes: stillness, synchronization, or generation. When the unit is turned on, the speed governor regulates the turbine speed from standstill to nominal speed, synchronizing it with the network's corresponding electrical frequency. The study's methodology must begin with the gathering and measurement of parameters from the hydropower station for characterization. Fuzzy logic software is the tool to use; it's a rule-based system that relies on the user's experience; it's a type of artificial intelligence software, and it's considered a subset of AI by computer engineers. The mode equation governing the Hydropower Generator Speed Controller is studied in the work [7].

The error is proportional to the integral of the error and the rate of change (derivative) of the error, and the controller is proportional to both. This algorithm is known as a PID controller (proportional integral derivative controller). This controller's general form is depicted in (1).

$$M(t) = k_p E(t) + k_i \int_0^1 E(t)\,\mathrm{d}t + k_d \frac{\mathrm{d}E}{\mathrm{d}t} \tag{1}$$

where: k_p is proportional constant; k_i is integral constant; k_d is Derivative constant; $E(t)$ is Error as function of time; $M(t)$ is controller output derivative. Equation (1) gives proportional action. Fuzzy LOGIC Controller would be introduce to elicit the required change in the control system.

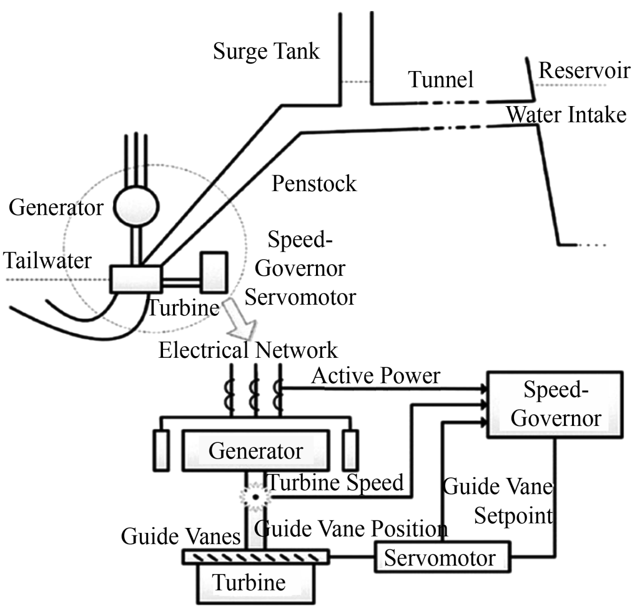

Figure 1. A typical layout of hydro electric power plant (Source: River Diversion Hydropower plant Hindawi.com).

2.1. Designing a Membership Function That Will Analyze the Causes of Slow Turbine Rotation

To provide the required output power, the Fuzzy Interference System (FIS) is initially built by providing the appropriate proportional electrical signal of two inputs, namely the first penstock and the second penstock. Hydro plants are utilized for peaking and baseload power generation, as well as pumped storage and spinning reserve power generation, particularly in a system with a large number of parts. In industries, frequency and voltage fluctuations are widespread; their stability determines the minimal standards that must be satisfied, resulting in a power quality rating. Effective plant usage necessitates complex control. The turbine speed governor is used in several ways by station automation to ensure optimal speed management; the necessity for a flexible governor design is crucial. Faulty turbine blades and good turbine blades are the variables needed to elicit the desired reaction, and the output is a membership function plot. The Fuzzy Logic Method is advantageous since it requires one or a big number of measurements or other assessments of the situations we wish to analyze and regulate. We then process all of these inputs using human-based, fuzzy If-then rules that may be expressed in plain English words. The last stage is weighting and averaging the results of all of the individual rules into a single output decision or signal that selects what to do or instructs a control system to do. The resulting signal is referred to as "defuzzified" since it is a crisp value. This design would analyze and guide us in determining whether the slow speed is due to a bad turbine blade or not; if a problematic turbine blade is discovered, the command would send a signal to the controller to take appropriate action for a positive reply (Figure 2).

2.2. Designing a Membership Function That Will Increase the Rotation of a Turbine

In this stage, the Fuzzy Interface System would be designed to give an indication

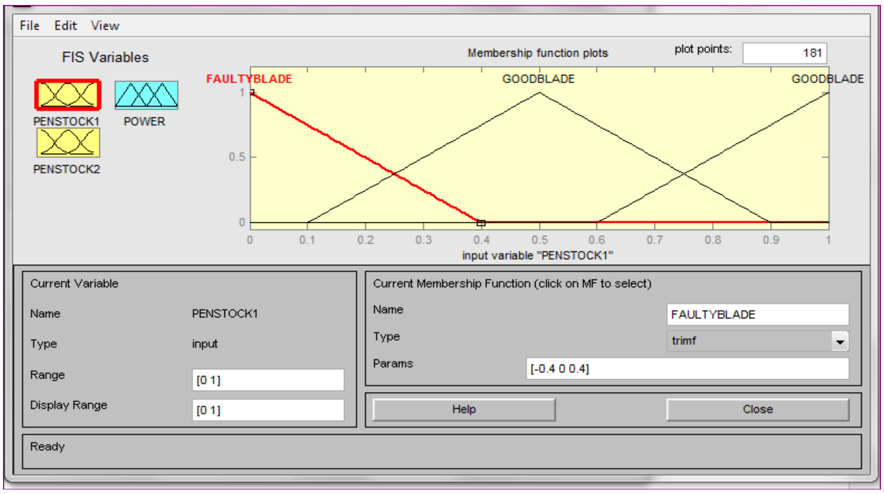

Figure 2. Designed membership function that will analyze the causes of slow turbine rotation.

of the cause of the problem and introduce the Fuzzy Logic in such a way that input variables to penstock number one and penstock number two should produce the desired mechanical output power using the input variables of slow rotation and high rotation. We know that for asynchronous alternating current generator, the generated Voltage (e.m.f) is directly proportional to the magnetic flux and the speed of rotation in revolution per minute (RPM) Equation (2)

$$E = k_1 \phi N \tag{2}$$

where E is the generated voltage k_1 represents machine constants; $k_1 = 2Zp/60cZ$ is the number of conductors in series per phase, p is the number of pairs of poles; c is the number of parallel paths in the armature. Whatever is done in any control system is the manipulation of the variables responsible for generating electromotive force in a generating plant, this depends on whether there are no defects on the machine constants (blades, conductors, etc.).

2.3. Designing a Fuzzy Rule That Will Generate Constant Power Supply When the Turbine Rotates Fast

A fuzzy logic controller's four fundamental components are fuzzification, rule basis, inference mechanism, and defuzzification. Using membership functions provided by fuzzy linguistic variables in the shape of a triangle, trapezoid, bell, or another suitable shape, the fuzzification converts its inputs into fuzzy values. The rule base incorporates the expert's linguistic descriptions as logical implications, such as IF x is positive, THEN y is huge. The inference mechanism evaluates fuzzy information in order to activate and apply control rules. The defuzzification procedure converts the inference mechanism into crisp values that can be applied to the actual system utilizing techniques such as the center of gravity, maximum, and weighted mean. The first input is the difference between the reference value, which is the desired output value, and the generator output value. The second input is the derivative of the mistake. An input stage, a processing stage, and an output stage make up Fuzzy Control Design. The input stage assigns membership functions and truth values to the sensor or other inputs such as relays, thumbwheels, and limit switches. Each appropriate rule is involved in the processing stage, which provides a result for each and then combines the outcomes of the rules. Finally, in the output stage, the combined result is converted back into a specific control output value. The triangle shape of the membership value would be employed in our design, however trapezoidal and bell curves might also be used; nonetheless, the shapes are often less significant than the number of curves required for their placement. In fuzzy jargon, three to seven curves are usually sufficient to encompass the desired range of an input value or the universe of discourse. Remember that the processing step is built on a set of logic rules expressed as IF-THEN statements, with the IF component referred to as the antecedent and the THEN part referred to as the consequent."

Typical fuzzy control systems have several rules. Considering this design.

The rules are stated thus:

1) If (Penstock 1 is faulty blade) and (penstock 2 is slow rotation) then (power is not constant);

2) If (Penstock 1 is good blade) and (penstock 2 is high rotation) then (power is constant);

3) If (Penstock 1 is good blade) and (penstock 2 is high rotation) then (power is constant);

4) If (Penstock 1 is good blade) and (penstock 2 is high rotation) then (power is not constant);

5) If (Penstock 1 is good blade) and (penstock 2 is slow rotation) then (power is not constant);

6) If (Penstock 1 is good blade) and (penstock 2 is high rotation) then (power is constant power);

7) If (Penstock 1 is good blade) and (penstock 2 is high rotation) then (power is constant power).

These are the rules that would be introduced in the design for the controller to give the expected result as shown in Figure 3 and Figure 4. Figure 5 shows the simulated result.

2.4. Designing a Model for Hydropower Generator Speed Control without Using Fuzzy Software Tool

The Fuzzy Logic Controller was used in this work to obtain optimal hydro turbine speed regulation. A multi-input and multi-output nonlinear controller for a system consisting of a hydraulic turbine and a synchronous generator coupled to an infinite bus is now installed. Sim Power Systems and Simulink blocks are used to simulate the entire system. The feedback linearization approach is used to control the controller. Its primary purpose is to manage the rotor angle as well as the terminal voltage, increase stability, and achieve a good dynamic response. The nonlinear controller's performance is evaluated using a nonlinear turbine-generator system. Simulink blocks are used to model the controller and turbine, while the generator is represented by the Synchronous Machine block

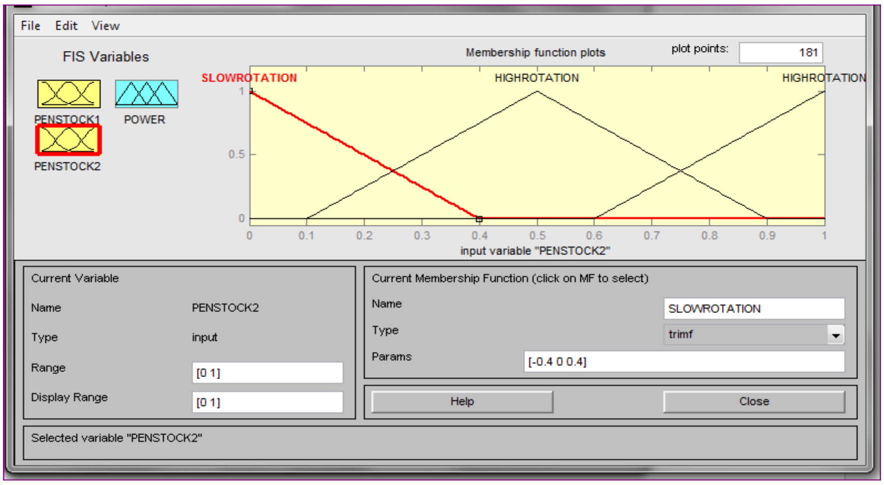

Figure 3. Designed membership function that will increase the rotation of a turbine.

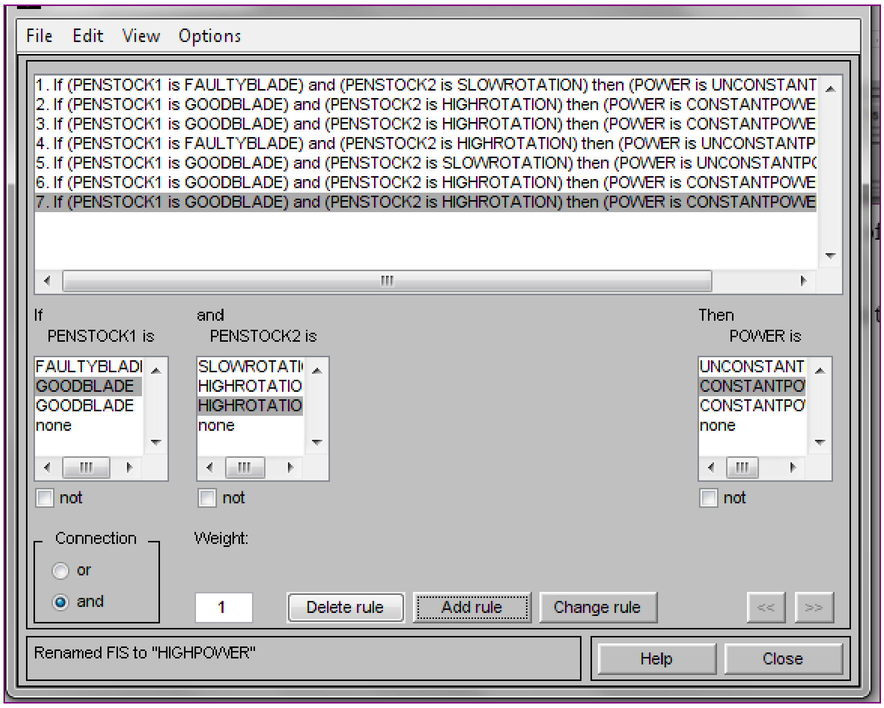

Figure 4. Designed fuzzy rule that will generate constant power supply when the turbine rotates fast.

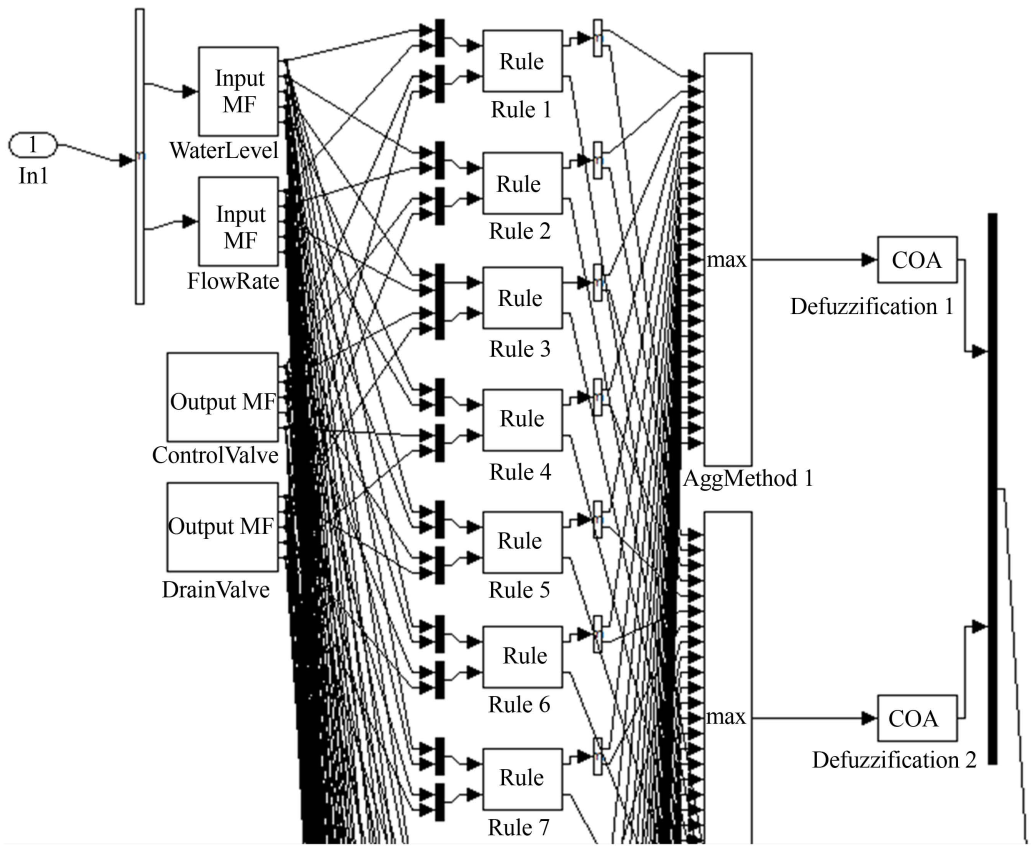

Figure 5. Simulated result of designed fuzzy rule that will generate constant power supply when the turbine rotates fast.

from the power lib package. Field voltage Ef, power angle delta, and terminal voltage Vt would all be monitored during the simulations. With the penetration of the fuzzy Logic Controller, Vt would be stabilized at the desired time interval. Because the time constant of the mechanical elements of the system is significantly bigger than the electrical time constants, it takes longer for the load angle to stabilize. The conventional controller will be substituted with the Fuzzy Logic Controller with the same excitation system and Hydraulic Turbine to examine whether there are any differences in the results with classical regulators with the same excitation (Figure 6).

2.5. Designing a Model for Hydropower Generator Speed Control Using Fuzzy Software Tool

The goal is to see if the design can be validated by seeing how long it takes to stabilize. To simulate the design in Simulink/Matlab, first, open the synchronous machine (SM) block menu and make sure that the machine beginning conditions (last line) are set to zero. Begin the simulation by connecting the Fuzzy Logic Controller to the (SPEEDTRONIC) electronic speed control module. When the SM initial conditions are incorrect, the simulation will not start in a steady state. As a designer, you should halt the simulation and begin initialization. You must first initialize the synchronous machine for the required purpose to begin the simulation in steady-state mode. Open the POWERGUI and select "Governing equations & Machine Initialization" as the test you want to run. The machine's "Bus type" should be set to the generator," indicating that the load flow/stability will be handled by the machine, which will regulate its active power and terminal voltage. Enter the computed parameters to specify the desired values. The turbine speed control module in this design accepts two signals as inputs to complement AND operations in Boolean algebra. As indicated in Figure 7, four output terminals are transmitted to the signal bus, resulting in a single output to affect the last command to the Hydropower penstock speed one.

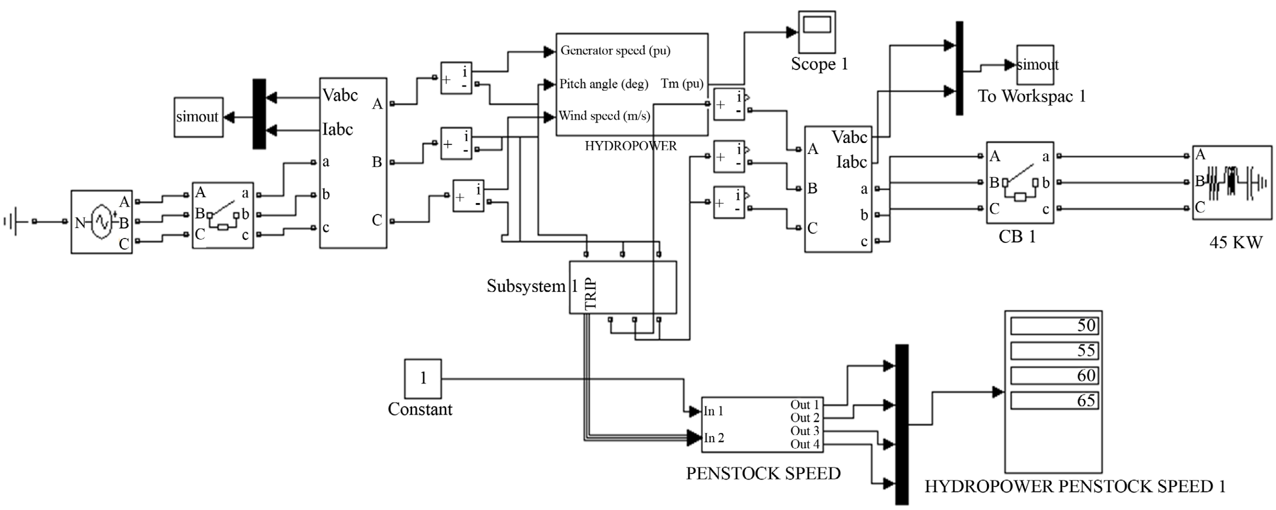

Figure 6. Designed model for hydropower generator speed control without using fuzzy software tool.

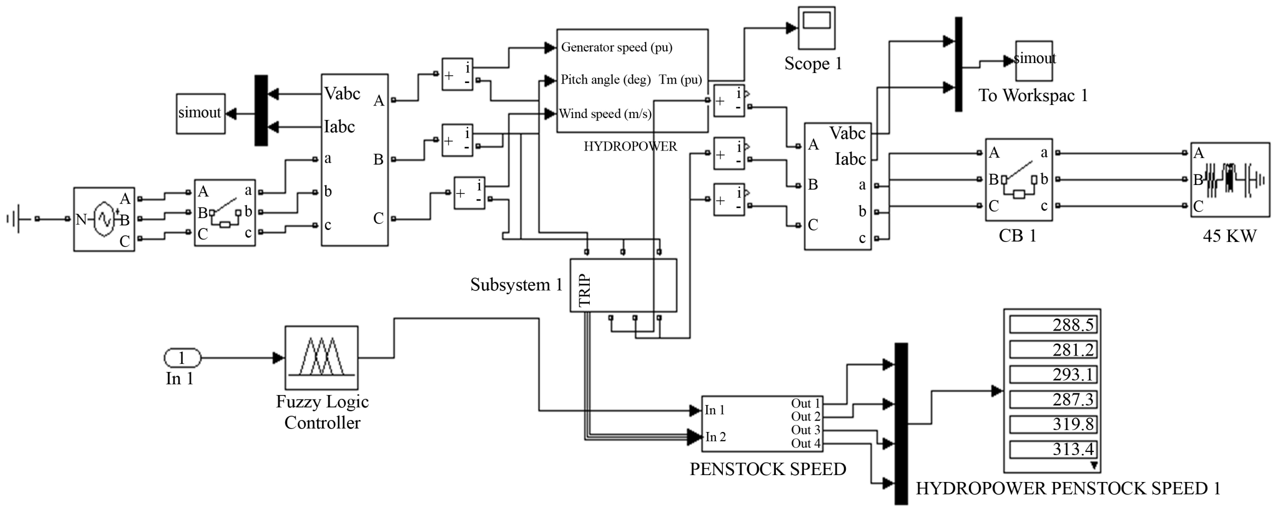

Figure 7. Designed model for hydropower generator speed control using fuzzy software tool.

3. Results and Discussion

The results of the simulations described in the methodology portion of this paper are presented here. Figure 2 shows the generated membership function for assessing the causes of sluggish turbine rotation when the turbine blade is faulty or good, using the Fuzzy Inference System.

Figure 3 shows a planned membership function that will increase the rotation of a Hydro Turbine Generator; the spinning of the turbine blade is high when it is not faulty, but slow when it is. Figure 4 depicts a newly designed fuzzy rule that creates a consistent power supply when the turbine rotates rapidly; it is a rule that sticks to the turbine's rapid rotation with rigor, resulting in a more stable power supply. When the turbine rotates swiftly, the created fuzzy rule creates a consistent power supply; this occurs when the rule is imbibed in the fuzzy block for its effective rise in turbine rotation and stable power supply. Figure 6 depicts a model for managing the speed of a hydroelectric generator that does not employ the fuzzy technique. The result is a decrease in the speed of the turbine, as seen in Table 1. Figure 6 shows a model for employing a fuzzy software tool to control the speed of a hydropower generator. As seen in Table 2, the effect is an increase in the turbine rotational speed, resulting in a more steady power supply. When a fuzzy logic controller is utilized, the outcome is a faster rotation of the rotor, resulting in a more stable power supply. Figure 8 shows a graph of the rotation speed of a hydro turbine generator vs time without the usage of a fuzzy controller. In terms of time coordinates, the maximum and lowest speeds of hydropower turbine rotation were (65, 4) and (50, 1), respectively. Figure 8 depicts the rotational speed of a hydropower turbine controlled by a Fuzzy Controller as a function of time. Figure 9 illustrates the highest speed of a hydropower turbine with Fuzzy vs time (319.8, 4) and the lowest speed of a hydropower turbine with Fuzzy vs time (319.8, 4), (319.8, 4), (1, 266.5). Table 3 is the comparison between Hydropower Turbine Rotation Speed Without and With Fuzzy Vs Time. Figure 10 depicts the outcome of hydropower turbine

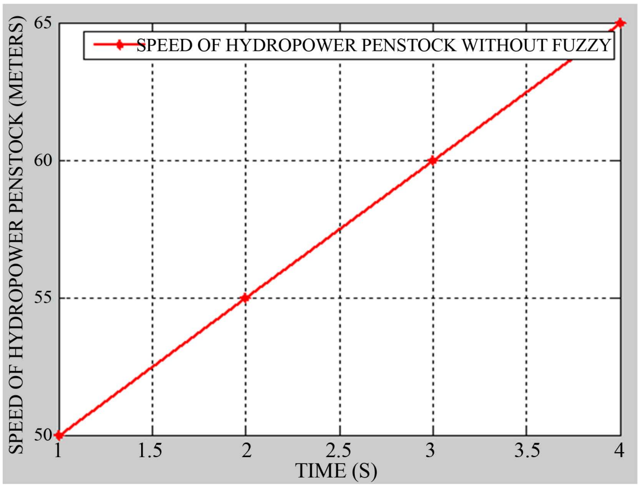

Figure 8. Hydropower turbine rotation speed without fuzzy versus time.

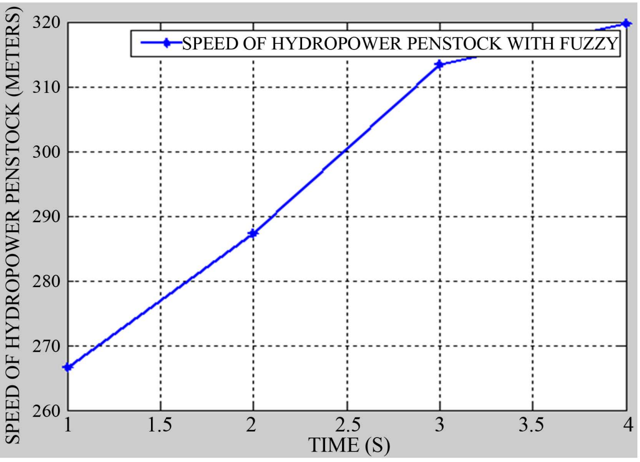

Figure 9. Hydropower turbine rotation speed with fuzzy versus time.

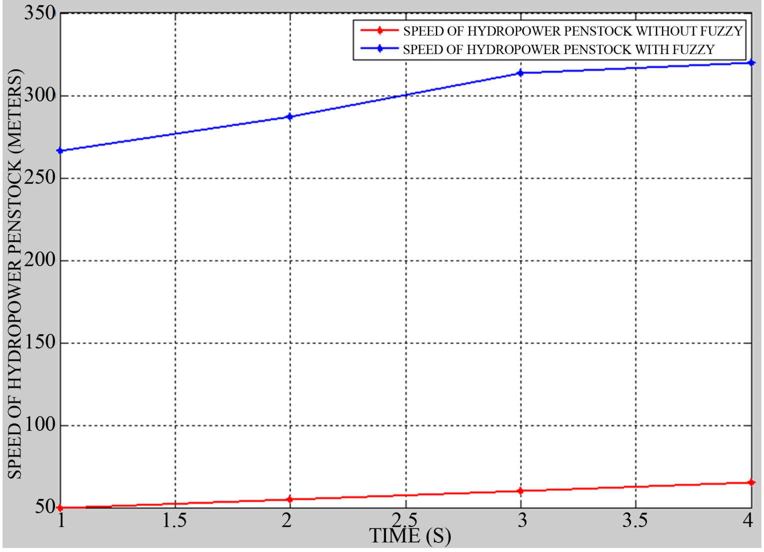

Figure 10. Simulated result of hydropower turbine rotation speed without and with fuzzy versus time.

Table 1. Hydropower turbine rotation speed without fuzzy versus time.

HYDROPOWER TURBINE ROTATION SPEED WITHOUT FUZZY	TIME (S)
50	1
55	2
60	3
65	4

Table 2. Hydropower turbine rotation speed with fuzzy versus time.

HYDROPOWER TURBINE ROTATION SPEED WITH FUZZY	TIME (S)
266.5	1
287.3	2
313.4	3
319.8	4

Table 3. Comparison between hydropower turbine rotation speed without and with fuzzy vs time.

HYDROPOWER TURBINE ROTATION SPEED WITHOUT FUZZY	HYDROPOWER TURBINE ROTATION SPEED WITH FUZZY	TIME (S)
50	266.5	1
55	287.3	2
60	313.4	3
65	319.8	4

rotation speed without and with fuzzy vs time. The results show that when the Fuzzy Logic Controller is used to control and regulate the turbine's speed, it rotates at a faster rate than when it is not. The results also show that while Fuzzy software enhances the reliability of power and voltage profile delivery, there is always the possibility of irregular power supply without it. The results showed that using a fuzzy logic controller improves the results and increases the hydropower's rotational speed.

4. Conclusions

Epileptic power supply in Nigeria has forced industrialists to rely on private diesel engines to generate their electricity; generating plants are old and in need of a total overhaul in hydropower stations; turbines are easily affected when the water level in the dam changes, resulting in low-speed rotation of hydropower turbines. This paper has presented an application of the Fuzzy software technique to overcome the problem by sequentially completing the stated objectives: designing a membership function to analyze the causes of slow turbine rotation, designing a membership function to increase the rotation of a turbine, designing a Fuzzy rule to generate constant power supply when the turbine rotates fast, and finally designing a model for Hydropower generation. A hydropower automatic speed governor is used to controlling the turbine output when a sudden load change occurs. This is to avoid the rotation speed of the turbine and generator to charge sharply due to load reduction or increase. Adjusting the water flow into the mini-hydro turbine makes the turbine output meet the change of external load. Due to the swiftness or fastness of the load changes in the generator, the artificial control method does not meet this requirement. This is why most hydropower stations are equipped with an automatic mechanical "governor" to regulate water flow through the penstock to the turbine blades. The simulation was performed using MATLAB 2007 Software to develop a fuzzy logic controller for hydropower Generator speed regulation with the aims of Stabilizing output power supply.

The result of the research shows the hydropower generator speed model which can be used to stabilized power output as a result of an increase in turbine speed rotation when the fuzzy logic controller is applied. The result showed that hydropower Generation speed regulation with and without fuzzy logic controller was 319.8 m/s and 65 m/s respectively. The speed increased by 254.8 m/s; the result shows that the application of fuzzy logic controller gives better result and increase the rotational speed of hydropower.

Conflicts of Interest

The authors declare no conflicts of interest.

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