THE USE OF SMART TURBINE TO ENHANCE THE CONTROL EFFICIENCY OF MICRO GRID POWER GENERATOR

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Abstract

This paper focuses on harnessing the potential of smart turbines to enhance the effectiveness of micro grid power generators. The key emphasis lies in exploring the integration of fuzzy logic, fuzzifier, defuzzifier, and rule-based selector in the design and control of smart turbines, with the ultimate goal of improving performance, stability, and efficiency in micro grid power generation systems. The fuzzy logic controller employed in this study utilizes various inputs, including turbine speed, water flow rate, generator voltage, grid frequency, and load demand, to generate appropriate control signals. To enable this process, the inputs undergo transformation into fuzzy sets using a fuzzifier. The fuzzifier converts crisp inputs into fuzzy values, assigning membership grades accordingly. By integrating fuzzy logic, fuzzifier, defuzzifier, and rule-based selector, the smart turbine becomes capable of making intelligent decisions based on real-time sensor data and predefined control rules. This comprehensive approach empowers the turbine to adapt its operations effectively and optimize energy generation within the micro grid power system. The experimental implementation and evaluation of the proposed approach demonstrate its effectiveness in achieving the desired control objectives. The utilization of fuzzy logic, in conjunction with the fuzzifier, defuzzifier, and rule-based selector, offers a robust and flexible solution for controlling smart turbines in micro grid power generators. Notably, the study's results showcase the significant improvement in hydropower turbine rotation speed, from 65m/s to 319.8m/s, when the water level reaches 4m on the dam.

Keywords: Smart Turbines; Generators; Fuzzy Logic; Fuzzifier; Defuzzifier; Grid

1. INTRODUCTION

Since the emergence of mankind on Earth millions of years ago, the consumption of energy has steadily increased to meet the growing demands for sustenance and well-being (Sivagami et al., 2020). This upward trajectory has been fueled by the continuous expansion of the global population, resulting in a surge in power requirements. However, it has become evident that the existing energy generation infrastructure is insufficient to meet the escalating power output needed (International Energy Agency, 2018; Okeniyi et al., 2018). To address this challenge, it is crucial to invest in the construction of new power generation facilities or explore alternative energy sources. Additionally, optimizing the efficiency, reliability, and cost-effectiveness of existing power plants has become a top priority for power generation companies and private operators to remain competitive (Mahmud et al., 2013).

While sustainable, renewable, and affordable energy technologies have gained renewed attention, turbomachines, powered mainly by fossil fuels, continue to be the primary choice for major energy producers worldwide (Ajayi et al., 2013). Nevertheless, concerns regarding the environmental impact of fossil fuel combustion emissions have prompted researchers and stakeholders to seek more efficient electric energy generation systems (Okeniyi, 2014). Turbomachinery-driven thermal power plants, including internal combustion, nuclear, gas turbine, and steam power plants, contribute approximately 80% of global electricity generation (Omosanya et al., 2019).

In the context of hydroelectric plants, precise control over frequency and power rating is essential for harnessing electric energy from water power. This control is achieved through the implementation of governor mechanisms. The primary objective of the governor system is to regulate the speed and power of the turbine by adjusting the water flow entering the turbine. When additional power is required, the governor opens the wicket gates, allowing a greater volume of water to access the turbine inlet. Conversely, when power demand decreases, the wicket gates are partially closed, limiting the water flow into the turbine. This control mechanism ensures the maintenance of the desired frequency (Omosanya et al., 2019).

As the power drawn from the turbine plant fluctuates, it directly affects the turbine's speed, resulting in changes to the output voltage and frequency. Increased power demand causes the turbine speed to decrease due to the load on the alternator, leading to a drop in voltage and frequency below the desired values. To restore the turbine to its normal speed, more water must be introduced into the system (Uddin et al., 2022). Conversely, when power demand decreases, the turbine speed increases due to reduced load on the alternator, resulting in higher voltage and frequency than the desired values. To rectify this, the water flow into the system must be reduced, which is achieved through an automatic control system (Amam and Zhang, 2021).

This control system comprises a sensor that measures the turbine speed and a mechanism that adjusts the water flow by opening or closing the wicket gate based on the sensor's feedback, thus maintaining a constant speed. Regulators, whether mechanical or electrical, are utilized to control the turbine speed. Throughout the history of hydraulic systems, regulators have been employed to regulate power output by managing the water flow to the turbine. The objective remains consistent, aiming to regulate the speed of the turbine shaft. Increasing power requirements involve opening the turbine inlet to allow more water, while decreasing power demands require narrowing the turbine inlet to restrict the water flow (Fangle and Guo, 2020).

Researchers have adopted various techniques to enhance power generation efficiency in micro-grid systems. However, despite the achievements made, turbine systems still face limitations in terms of maintaining stability. Therefore, this paper proposes the implementation of a smart turbine system to improve power generation efficiency and ensure stability

2. LITERATURE REVIEW

Sivagami et al. (2020) conducted a study exploring the application of wind turbine and solar energy for power generation. The study utilized wind turbine energy generated by small and large pulleys, batteries, and flat belts placed alongside a highway. Additionally, solar panels were installed to harness solar energy. The results indicated that this technique could generate a significant amount of energy. However, the performance of the turbine system could be enhanced by incorporating intelligent techniques to manage turbine impacts and conserve energy.

Uddin et al. (2022) introduced a smart vertical axis highway wind turbine in their research. This system aimed to harness wind energy from the environment along a highway path. The vertical axis turbines were positioned between the road lanes to capture wind from both sides, thereby maximizing the effectiveness of wind speed on the turbines. The study demonstrated that the turbine operated at an average of 4 to 5 hours per day at full output capacity. However, the power supply during this operation could be further improved by implementing smart turbine technologies to maintain a consistent speed.

Küçükerdem and Yilmaz (2015) proposed a smart turbine speed regulator specifically designed for hydroelectric plants. The turbine system consisted of a control unit that evaluated blade parameters to control the flow rate, motors, sensors, and a tachometer to monitor speed information, amplitude, and frequency of the generated electric energy. These parameters facilitated the adjustment of blade positions to match the reference inlets. The study demonstrated that the system maintained the alternator frequency within the range of 49.8Hz to 50.2Hz. Sharma and Madawala (2012) investigated the concept of a smart wind turbine system. Their system introduced the SmartBlade, which utilized variable length blades and a hybrid mechanical-electrical power conversion system. The variable length blades extended when the turbine speed dropped below a rated speed, effectively increasing the blade area and maintaining a relatively high power output. The study revealed that the system achieved a voltage boost of up to 106V using wind inductance from the SmartBlade technology. Omosanya et al. (2019) provided an overview of improving power generation efficiency in steam turbines. Their study specifically focused on the last stage low-pressure turbine blades to analyze the parameters influencing power generation efficiency in turbine machines during electricity generation. Experimental tests were conducted using a turbine machine at the Egbin thermal power station in Nigeria. The results emphasized that optimizing design parameters such as rotational speed, blade length, chord length, Reynolds number, velocity, and coefficient of viscosity or friction could enhance turbine power efficiency.

3. DESIGN METHODOLOGY

The methodology of this system involves two fuzzy input variables. The algorithm utilizes five triangle membership functions within a scale range of 0 m to 20 m for the water level input and 0 (m^3/s) to 100000 (m^3/s) for the flow rate input. The five fuzzy membership functions for the water level input are defined as follows: very low (0-5 m), low (0-10 m), below danger (5-15 m), danger (10-20 m), and over danger (15-20 m). Similarly, the five fuzzy membership functions for the flow rate input are defined as extremely slow (0 m^3/s - 1-25000 m^3/s), slow (0 m^3/s - 50000 m^3/s), normal (25 m^3/s - 75000 m^3/s), quick (500 m^3/s - 100000 m^3/s), and very fast (75000 m^3/s - 100000 m^3/s). The system outputs are the drainage valve and the control valve for release. The five membership functions representing the output control valves for drainage and release are defined as entirely closed (0-5), 25% opened (0-50), 50% opened (40-60), 75% opened (50-90), and fully opened (70-100).

Figure 1 illustrates the schematic layout of the hypothetical hydroelectric power station. Water level and flow rate devices are employed to monitor the water condition in the plant. The measured values are then connected to the two fuzzifiers of the fuzzy logic control scheme after appropriate amplification and voltage adjustment. The outputs of the system are the drainage valve and the releasing control valve, which are obtained through defuzzification (Abbas, 2011).

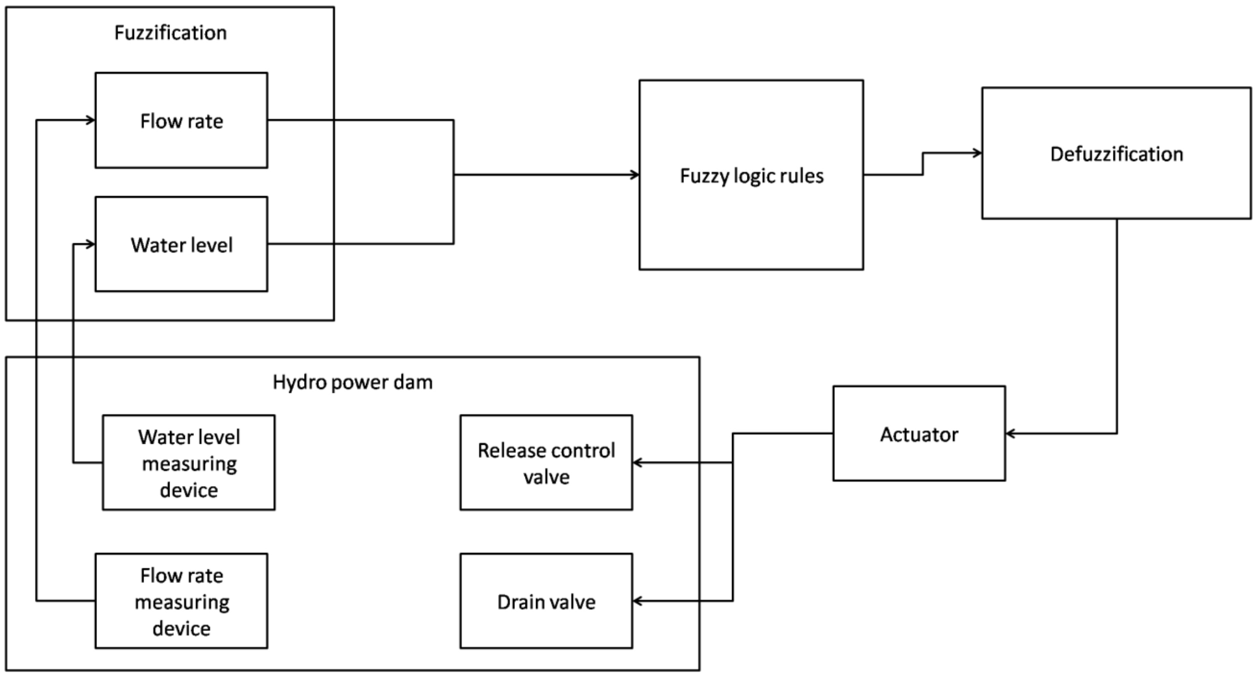

Figure 1: Block Diagram of Hydro-Electric Power Dam fuzzy control system

3.1 Fuzzifier

To generate linguistic values for each input variable for the inference engine, the fuzzifier compares the input crisp values to a set of levels. Fuzzy concepts, implication, and inference rules are used by the fuzzy logic-based inference engine to emulate human decision-making.

3.2 Inference Engine

Four AND operators in the inference engine choose the minimum value input for the output. This inference engine uses the four inputs from the fuzzifier and the min-max composition to produce the output R values. The min-max inference technique employs the min-AND action between the four inputs. This kind of inference procedure is illustrated in Figure2.

The number of active rules is equal to mn where m is the highest amount of overlaid fuzzy sets and n is the number of inputs. There are 25 active rules in total in this design with m = 5 and n = 2. The sum of the number of rules is equal to the product of the number of functions and the working range of the input variables.(Genet, 2017). Five membership functions made up the two input variables that are described here. As a result, 5 × 5 = 25 rules were needed, which are represented in Table 1.

Table 1: Total Number of Rules

INPUT	Parameters	OUTPUT	Parameters
Water Level (m)	Flow Rate (m^3/s)	Out-flow valve	Drain Valve
Very Low	Very slow	Fully closed	Fully closed
Very Low	Slow	Fully closed	Fully closed
Very Low	Normal	Fully closed	Fully closed
Very Low	Fast	Fully closed	Fully closed
Very Low	Very Fast	Fully closed	Fully closed
Low	Very slow	Fully closed	Fully closed
Low	Slow	Fully closed	Fully closed
Low	Normal	Fully closed	Fully closed
Low	Fast	Fully closed	Fully closed
Low	Very fast	Fully closed	Fully closed
Below danger	Very slow	Fully closed	25% opened
Below danger	Slow	25% opened	25% opened
Below danger	Normal	25% opened	25% opened
Below danger	Fast	50% opened	50% opened
Below danger	Very fast	50% opened	75% opened
Danger	Very slow	50% opened	50% opened
Danger	Slow	50% opened	50% opened
Danger	Normal	75% opened	Fully opened
Danger	Fast	75% opened	Fully opened
Danger	Very fast	75% opened	Fully opened
Above Danger	Very slow	75% opened	75% opened
Above Danger	Slow	75% opened	Fully opened
Above Danger	Normal	Fully opened	Fully opened
Above Danger	Fast	Fully opened	Fully opened
Above Danger	Very fast	Fully opened	Fully opened

Only four rules are required in this scenario for the particular values of the two variables since each value of the two parameters in a zone map to a mapping of two functions. The 4 rules were established using the appropriate mapping parameters of f1 [3], f1[4], f2[2], and f2[3]. Here, the definition of f1 [3] is the appropriate mapping value of the membership function "Below Danger" of the water level in region-3, and the others are defined similarly. (Fangle, 2020).

$$R_1 = f_1 \wedge f_3 = f_1[3] \wedge f_2[4] = 0.4 \wedge 0.2 = 0.2$$

$$R_2 = f_1 \wedge f_4 = f_1[3] \wedge f_2[5] = 0.4 \wedge 0.8 = 0.4$$

$$R_3 = f_2 \wedge f_3 = f_1[4] \wedge f_2[4] = 0.6 \wedge 0.2 = 0.2$$

$$R_4 = f_2 \wedge f_4 = f_1[4] \wedge f_2[5] = 0.6 \wedge 0.8 = 0.6$$

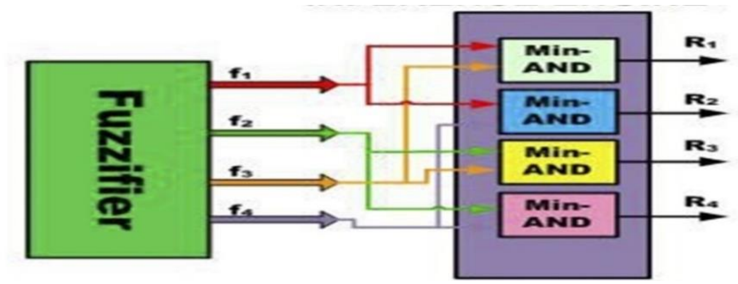

Plate 2: Inference Engine Block Diagram

3.3 Rule Selector

The water level and flow rate are provided in two distinct values to the rule selector. Given algorithmic principles applied to the design model, it provides singleton values of output functions. For two variables, Table 2 lists the four rules that must be followed in order to find the singleton values S1, S2, S3, and S4 for each variable.

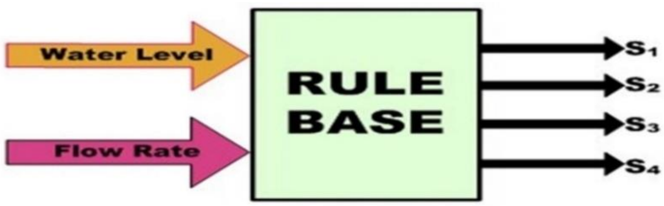

Figure 3: Rule Base Selector

Table2: Rules Applied Model Illustrations

Rule No.	Input		Singleton values of output		
	Water level	Flow Rate	Release Control valve	Drainage valve	Singleton values
1	Below Danger	Fast	0.50=50% opened	50% opened = 0.50	S_1
2	Below Danger	Very Fast	0.50=50% opened	75% opened = 0.75	S_2
3	Danger	Fast	0.75=75% opened	Fully Opened =1.0 %	S_3
4	Danger	Very Fast	0.75=75% opened	Fully Opened =1.0 %	S_4

The rule base receives two unique input values, splits the discourse universe into regions with two fuzzy variables in each area, fires the rules, and produces singleton values for each output variable. Figure 3 shows the main block diagram of the Rule Base.

3.4Defuzzifier

Two defuzzifiers regulate the actuators in this system; Release (Valve Control and Drainage Valve). Figure4 to 6 display the member-ship functions of the two output variables, and Table 3 provides details for each plot.

Table 3: Output Variables Membership Functions

MFs	Range	Release valve	Drain Valve
MF_1	0-5	Fully Closed	Fully Closed

MF_2	0-50	25% Opened	25% Opened
MF_3	40-60	50% Opened	50% Opened
MF_4	50-90	75% Opened	75% Opened
MF_5	70-100	Fully Opened	Fully Opened

After estimating its inputs, the defuzzification process produces outputs with crisp values. In this setup, each of the two defuzzifiers receives 8 inputs. In plate 3.8, four values of R1, R2, R3, and R4 from the inference engine's outputs and four values of S1, S2, S3, and S4 from the rule selector are displayed. Each defuzzifier uses the mathematical formula $\sum Si * Ri/\sum Ri$, where i is a number between 1 and 4, to estimate the crisp value produced using the centre of average (C.O.A) approach. Each output variable membership function plot consists of five functions with a similar range of values in order to make things simpler. (Barati, 2016).

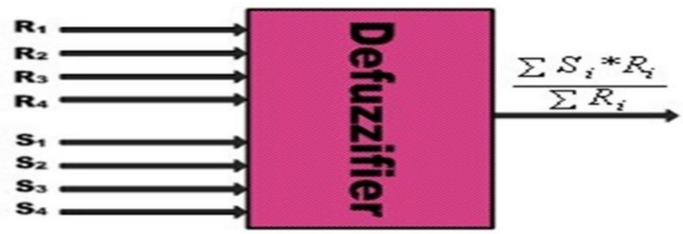

Figure4: Defuzzifier Block Diagram

Figure4 depicts the defuzzifiers' design layout. A single defuzzifier includes: one adderfor $\sum$ Ri,four multipliers for the product of Si*Ri, one adder for $\sum Si * Ri$, and one divider for $Si * Ri/\sum Ri$. Finally, a defuzzifier gives the estimated crisp value output.

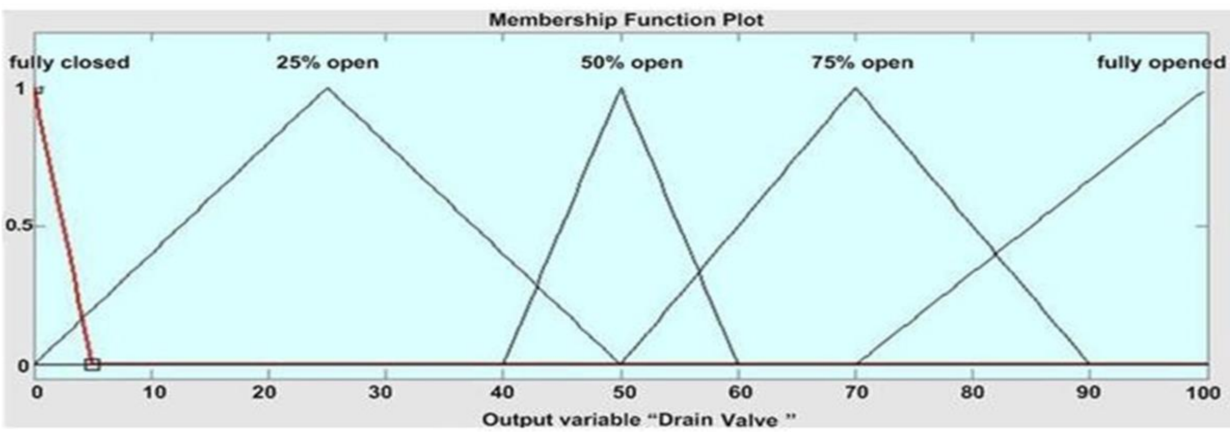

Figure 5: Graph of Membership Functions for Output Variable, "Drain Valve"

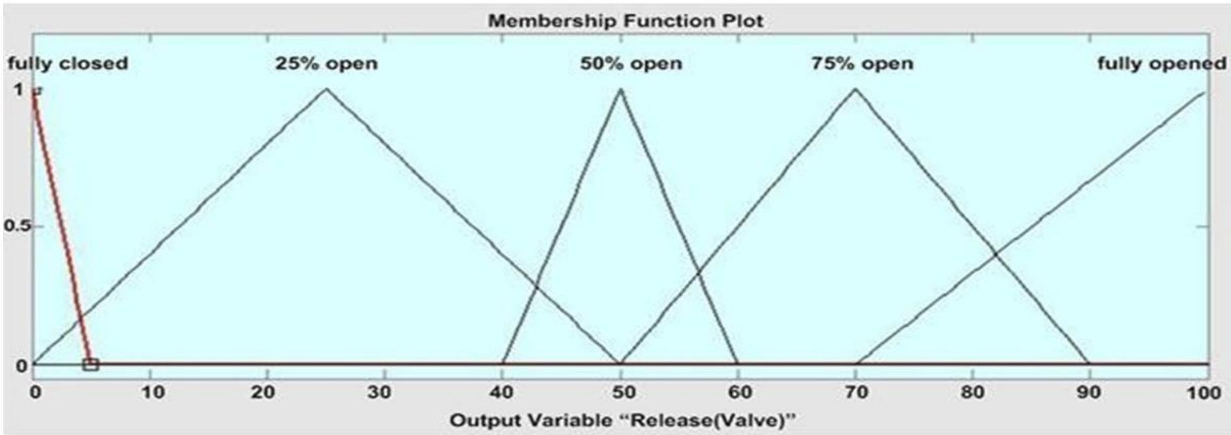

Figure 6: Graph of Membership Functions for Output Variable, "Release (Valve Control)"

3.5 **Fuzzy Logic Controller Design**

Mamdani's fuzzy inference method was chosen for the design of the fuzzy logic controller in this dissertation to control the frequency of the micro hydro power plant. The controller steps were specifically designed with Mamdani's fuzzy inference method in mind, including defuzzification, fuzzy inference, fuzzy rules, and fuzzy inference. The work by Genet (2017) provided insights into the development of the fuzzy controller.

In order to create a reliable and intelligent fuzzy controller, the design process considered the following aspects:

Control engineering expertise and understanding: The design took into account the knowledge and understanding of control engineering principles.

Operator control observations: A log book or observations of control operations by an operator were used to infer fuzzy if-then rules, expressing the input-output relationships.

Fuzzy process model: A fuzzy control rule base was developed based on an inverse model of the regulated process. This approach provided explicit solutions, particularly for low-order systems, if both fuzzy models for open and closed-loop systems were available. Alternatively, fuzzy models for control or fuzzy identification could be utilized.

Knowledge-based approach: The design considered the use of self-organizing controllers that develop their own rules, as well as neural networks.

Non-linear nature of fuzzy control: Fuzzy control lacks traditional design techniques such as root-locus, frequency response, pole placement, or stability margins due to the non-linear nature of the rules.

The suggested fuzzy controller was designed to dynamically adjust the proportional gain Kp and integral gain Ki of a PID controller based on the frequency error e and the speed change e. The reference values Kp* and Ki* were added to determine Kp and Ki, respectively. These reference values served as the controller's inputs. (Genet, 2017).

The next step in the fuzzification process involved selecting appropriate membership functions for the inputs and outputs. Each linguistic variable was associated with a fuzzy set, with the degree of membership indicating the extent to which an element belongs to that set. The transition from membership to non-membership was designed to be progressive rather than sudden. The support of a fuzzy set included the elements with non-zero memberships. Membership functions were used to link a number to each element of the universe. While the choice of form and width is arbitrary, general principles were followed. The design process involved trial and error, conducting multiple simulations to determine the universe of discourse and the structure of the membership functions. Triangular and trapezoidal shapes were employed for the membership functions of all input and output variables. (Ross, 2020).

4. MODELLING OF HYDROPOWER GENERATOR SPEED CONTROLLER

The integral of the error, the rate of change (derivative) of the error, and the actual error all have an impact on the controller. A PID controller is the name given to this method (proportional integral derivative controller). Equation shows the general form of this controller

$$M(t) = K_p E(t) + K_I \int_0^t E(t)dt + K_d \frac{dE}{dt} \quad (1)$$

Where:

K_p is proportional constant, Ki is integral constant, K_d is Derivative constant, E(t) is Error as functionoftime, M(t) is controller output derivative.

Proportional action is provided by equation (1). The output of the controller's second equation is always equal to the integral of the error.

This implies that the controller output will keep changing as long as the errors deviate from zero.

The physical potential of the algorithm should be taken into account when the controller output is immutable. Without integral action, the proportional constant is made absurdly large, and unless this condition changes, the process output never approaches the set point. Whenever the rate of change of error is non-zero, a component of the output is provided by the controller's final equation. Therefore, when the process readings are faulty, the derivative mode predicts the mistake at a faster response time.(Barati, 2016).

The following is (1)'s discrete or digital equivalent:

$$M_i = K_p \sum_{j=1}^{i} E_i + \frac{K_D}{T}(E_i - E_{i-1}) \quad (2)$$

Where:

T is sampling interval, E_i is Error at i^{th} sampling interval, E_{i-1} is Error at previous sampling interval

$$Mi = Kp1 + \frac{K_D}{T} Ei - \frac{K_p K_D}{T} Ei - 1Mi = Kp1 + \frac{K_D}{T} Ei - \frac{K_P K_D}{T} Ei - 1 + (TK_p K_i)Si \quad (3)$$

And S_i is the sum of error.

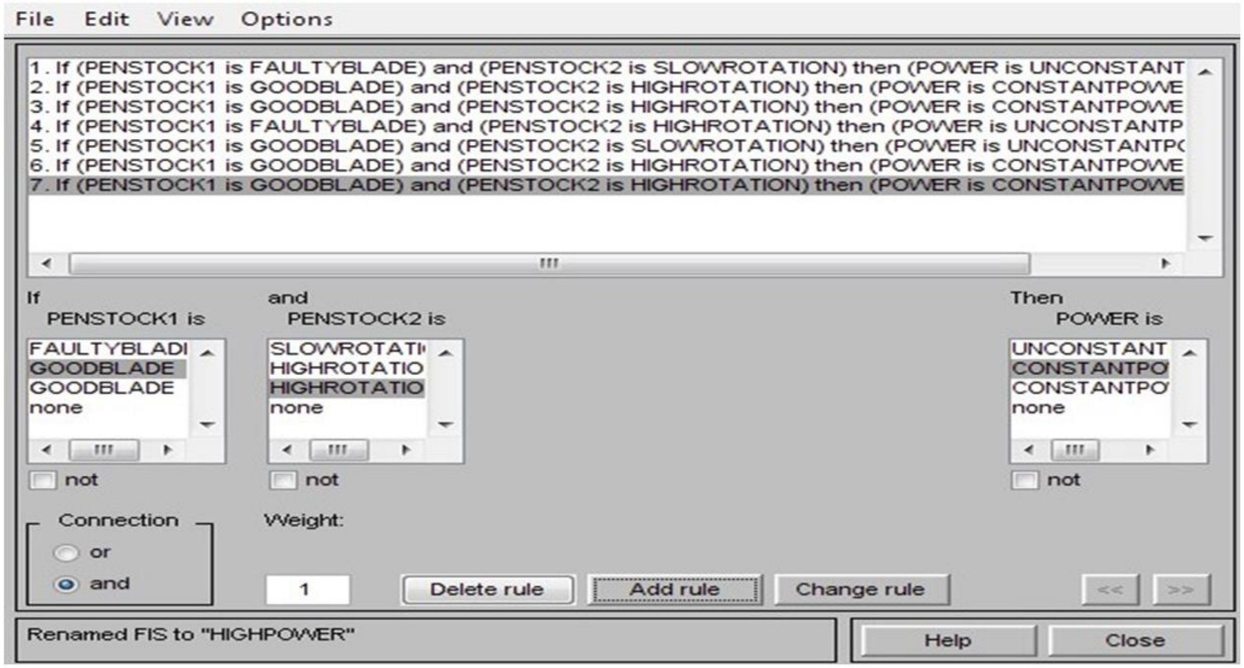

Figure 7: Designed fuzzy rule that will generate constant power supply when the turbine rotates fast.

5. SYSTEM IMPLEMENTATION

In the implementation of the smart turbine controller in a macro grid power generator, several steps are followed to ensure its successful integration and operation (Sivagami et al., 2020). Firstly, the fuzzy controller is integrated with the turbine control system and relevant hardware components, establishing seamless communication and coordination between them. Sensors are then installed to measure crucial parameters such as turbine speed, water flow rate, generator voltage, grid frequency, and load demand, providing real-time data for decision-making purposes. To process and utilize the sensor data effectively, a data acquisition system is implemented to collect and process the information, extracting meaningful insights to support the operation of the fuzzy controller. Communication and networking capabilities are established to facilitate interaction and coordination between the smart turbine controller and other components within the macro grid power system. Extensive testing and validation are conducted under various operating conditions, load scenarios, and grid conditions to evaluate the performance of the controller against defined objectives and stability criteria. This ensures that the smart turbine controller operates efficiently and reliably. To maintain optimal performance, a monitoring and maintenance system is implemented to enable real-time performance monitoring, fault detection, and regular upkeep of the smart turbine controller.

By following these steps, the smart turbine controller was successfully integrated into the macro grid power generator, leading to improved control, stability, and efficiency in power generation. The implementation process often involves the use of MATLAB Simulink to simulate the operation of the Micro Hydro-Power Plant (MHPP) by modeling its components. The Simulink model allows for the evaluation of the MHPP's performance using a PID controller, testing its operation with the recommended Fuzzy Logic Controller, and modeling the mechanical energy of the turbine.

6. RESULTS AND DISCUSSION

This section illustrates the results of a built fuzzy rule that will produce a steady supply of electricity when the turbine rotates quickly. This demonstrates a fuzzy rule that firmly adheres to the turbine's rapid rotation in order to improve a reliable power supply and generator efficiency.

Water level is plotted against hydropower turbine rotation speed in Figure 8. The hydroelectric turbine rotation speed versus water level coordinate reached its maximum at (65 m/s, 4 m) and its minimum at (50 m/s, 1 m), respectively. This demonstrates the favourable correlation between water level and hydroelectric penstock speed (m/s) (m).

Hydropower turbine rotation speed is plotted against water level in Figure 9. The results show that (319.8 m/s, 4 m) was the speed of the hydropower turbine with fuzzy verses water level, and (266.5 m/s, 1 m) was the speed with the least amount of fuzzy.

Therefore, the water level needed for the rotating speed of hydropower increases as the speed of the penstock increases.

Comparative results for speed of rotation of a hydropower turbine with and without fuzzy versus water level are shown in Figure 10. The outcome demonstrates that fuzzy increases the turbine's rotational speed compared to no fuzzy. The outcome also demonstrates that fuzzy improves consistent power supply, whereas intermittent power supply results from no fuzzy. This displays the stabilized power output as a result of the implemented fuzzy logic controller's increased turbine rotation speed. The outcome demonstrates that using a fuzzy logic controller improves results and speeds up hydropower rotation.

Table 4: Hydropower Turbine Rotation Speed Without Fuzzy Vs Water Level

Hydropower turbine rotation Speed without fuzzy(m/s)	Water level (m)
50	1
55	2
60	3
65	4

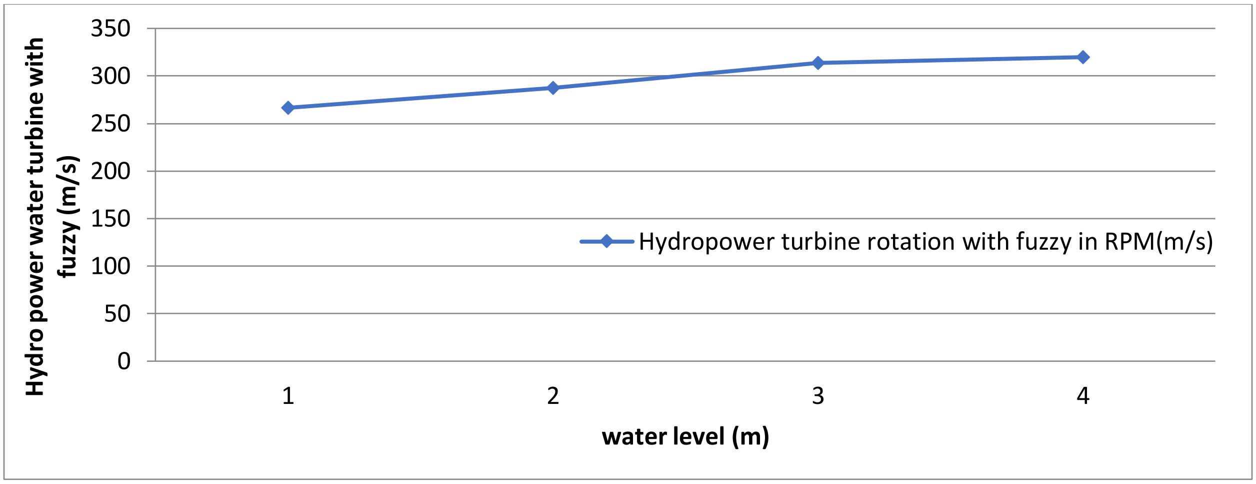

Figure 8: Hydropower Turbine Rotation without Fuzzy Vs Water Level

Table 5: Hydropower Turbine Rotation with Fuzzy vs Time

Hydropower turbine rotation with fuzzy in RPM(m/s)	Water level (m)
266.5	1
287.3	2
313.4	3
319.8	4

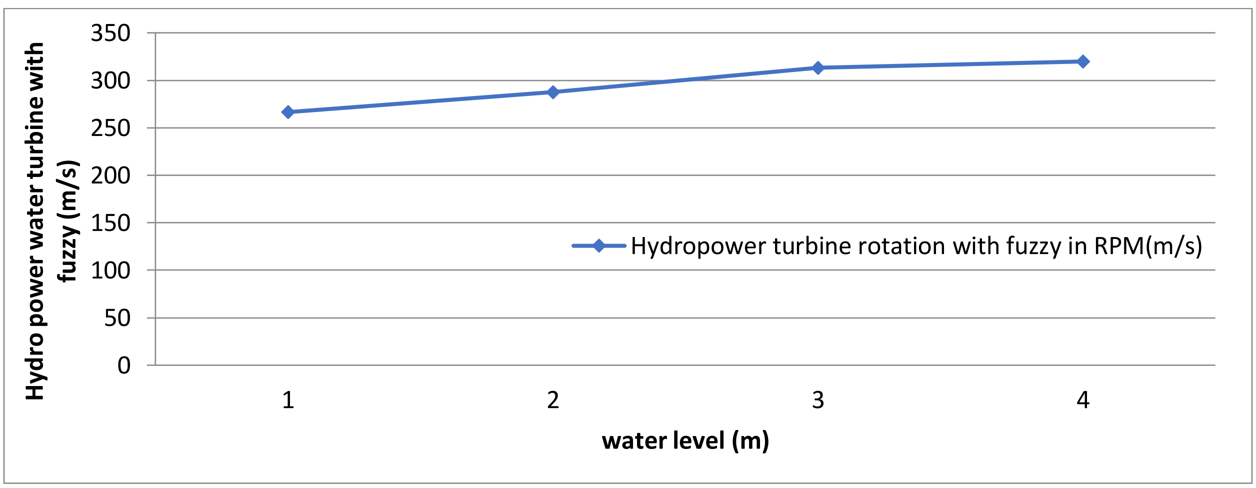

Figure 9: Hydropower Turbine Rotation with Fuzzy Vs Water Level

Table 6: Comparing Hydropower Turbine Rotation Speed Without and with Fuzzy vs Water Level

Hydropower turbine rotation speed without fuzzy(m/s)	Hydropower turbine rotation speed with fuzzy(m/s)	Water level (m)
50	266.5	1
55	287.3	2
60	313.4	3
65	319.8	4

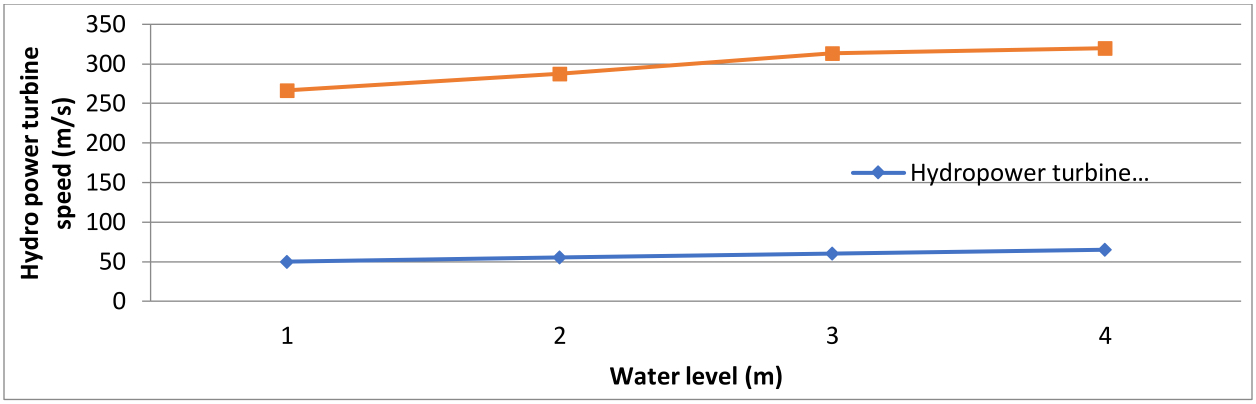

Figure 10: Comparative Result of Hydropower Turbine Rotation Speed without and with Fuzzy vs Water Level

The controller was tested to determine how well the FLC minimized the impact of speed variation on the controlling device and other components, which are speed deviation sensitive. High water flow rates allow the system to generate more power and provide all loads with power. Whenever the flow rate is low and a sizable client load is added to the system, speed variation will cause damage to the regulating device and other components. The controller separates all loads from the network aside from controller load in order to safeguard these components, which are significantly influenced by speed variation. In order to safeguard the component, the controller divides all loads or a subgroup of loads in accordance with the rate of water flow.

7. CONCLUSION AND RECOMMENDATION

There are rural areas with rivers that are primarily used for agricultural purposes, but these rivers also hold potential for small-scale hydroelectric power generation. In many rural communities, access to energy is still lacking, making these rivers valuable resources for producing limited amounts of hydroelectricity. The objective of this dissertation was to utilize these existing hydropower resources and develop a cost-effective controller for micro hydropower generation in rural areas. One challenge encountered in micro hydro power plants (MHPP) was frequency modulation issues when there was a change in load. To address this, the suggested approach employed a fuzzy logic controller to enhance and maintain frequency regulation in the MHPP. The controller's flexibility allowed it to be adapted to micro hydro power plants with different power outputs and head by adjusting the size of the actuator valve. Additionally, by expanding the number of membership functions, the system was able to achieve stable and responsive performance at various operating points.

The focus of the study was on the cost-effectiveness of the system, as it utilized an induction generator instead of a synchronous generator. This choice offered advantages in terms of cost, durability, ease of starting, and control. The study's results demonstrated that the application of the fuzzy logic technique significantly improved the rotation speed of the hydropower turbine, increasing it from 65m/s to 319.8m/s when the water level was at 4m high on the dam.

Based on the findings, a recommendation is made for the Nigerian government to prioritize the development of micro hydropower generation, considering that many villages, particularly those located in highlands, still lack access to electricity despite having abundant resources. It is suggested to explore other renewable energy sources such as wind and solar energy production alongside micro hydropower plants to address rural electrification needs. This would allow for further investigation into the performance of fuzzy logic controllers in various energy generation scenarios.

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