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An Automatic Wind Turbine Braking System on PLTH Bayu Baru through a Fuzzy Logic Controller

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A B S T R A C T

PLTH Bayu Baru is one of the hybrid power plants (HPP) located in Baru beach, Pandansimo, Bantul, Yogyakarta, Indonesia. It generates electrical energy from two sources, wind and solar energy. However, a problem is encountered regarding wind turbine mechanics due to using a manual switch for braking during periods of excessive wind speed. This study proposes an automatic wind turbine braking system through a utilized fuzzy logic controller (FLC) for the PLTH Bayu Baru application. The Mamdani type FLC without complex mathematical models is applied to the Arduino Uno development board to realize the proposed systems. The error (*Error_V*) and delta error (*dError_V*) values from the generator voltage sensor become the input of the proposed systems, while the pulse width modulation (PWM) becomes the output for controlling the on/off period of the MOSFET as switching devices. The proposed systems have been tested on a micro-scale wind turbine with PMSG 12V/400W type. From the testing results, the proposed system successfully braked automatically at the point wherein the generator voltage exceeds the setpoint value. Also, the proposed system keeps the generator voltage less than 13.8V, so the problem caused by excessive speed can be resolved.

INTRODUCTION

Renewable energy sources (RES) promise to produce electrical energy with clean sources [1]. It can be conducted from solar energy, wave energy, wind energy, hydropower, and other sustainable energies. Among these energies, wind energy is one potential RES. Wind energy utilization is carried out by implementing wind turbine power plants. Also, it can be conducted by integrating with other RES power plants so formed in a hybrid power plant (HPP) [2].

PLTH Bayu Baru, located in the coast of Baru beach, Pandansimo, Bantul, Yogyakarta, is one of the HPP in Indonesia. It utilizes wind energy and solar energy with 60 kW and 27 kW capacity. This power plant is a form of Regional Innovation System (SIDa) initiated by the Ministry of Research and Technology (Kemenristek) Indonesia in collaboration with related institutions, which becomes one of the power plants based on RES to support the national energy mix in Indonesia [3].

The generated electricity by PLTH Bayu Baru utilizes for street lighting, making ice cubes, and culinary stalls [4]. However, various problems are encountered during the operation process in energy storage (battery), wind turbine mechanics, and the braking system. In [5] mentioned that the possible problems is caused by excessive wind turbine rotation. The over-speed wind turbine rotation led to the generator voltage, which exceeded the limit of the storage system used. Also, it led to damage to the shaft and bearings of a wind turbine.

There are three wind turbine braking mechanisms, namely aerodynamic, mechanical, and electric braking, to overcome the mentioned drawback. Aerodynamic braking includes controlling the pitch angle, passive stall, and furling/active stall against incoming wind energy. Meanwhile, mechanical braking involves controlling turbine speed using friction from a brake disc [6]. Furthermore, electrical braking is carried out by utilizing the magnetic field interaction between the permanent magnet and generator winding, for example, short-circuiting the generator output line using a switch [7].

In practice, the development of braking systems has been proposed by researchers. Study [8] proposed an electromechanical braking system for a 3 kW vertically axial wind turbine power plant followed by mathematical modelling. Furthermore, [9] proposed economic and safe braking systems employing PWM braking circuits with the FETs control circuit.

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Meanwhile, the proposed robust braking systems are based on the chopper circuit in the PMSG wind turbine introduced by [10]. Referring to the existence of PLTH Bayu Baru, which employs PMSG in wind turbine power plants. It should be evaluated periodically because the generator components are majority placed in the field [11]. Also, PLTH Bayu Bayu still uses an electric braking system with a manual switch. It works by short-circuiting the generator output and utilizing the magnetic field interaction between the permanent magnet and winding. However, applying manual switches harm wind turbines due to the rapid rotating condition of the turbine, which damages the generator windings during sudden brakes.

This study proposes an automatic wind turbine braking system based on the fuzzy logic controller (FLC) to replace manual switching in PLTH Bayu Baru with PMSG 12V/400W type. The Mamdani type FLC without complex mathematical models is applied to the Arduino Uno development board to realize the proposed systems. It works automatically when the generator voltage exceeds the setpoint value to avoid problems caused by excessive wind turbine rotation.

METHOD

Wind Turbine Generator Specifications

PLTH Bayu Baru generates electricity from two RES, wind energy and solar energy. The automatic braking system proposed in this study is dedicated to the 60 kW wind turbine generator of the PLTH Bayu Baru. The construction wind power plant in PLTH Bayu Baru is illustrated in Figure 1.

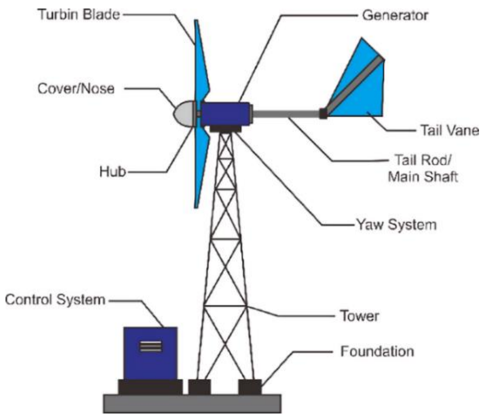

Figure 1. The Construction of Wind Power Plant PLTH Bayu Baru

This wind turbine power plant is categorized in small-scale generation with low-wind speed. Therefore, it is generally applied permanent magnet to convert mechanical power into electrical power wherein it has advantages due to the creation of magnetic flux without energy. Figure 2 shows a generator turbine from RoHS used on PLTH Bayu Biru with the specifications listed in Table 1.

Figure 2. Generator Turbine on PLTH Bayu Baru

Table 1. Generator Specifications

Parameters	Specifications
Brand and type	W400 Small Wind Turbine
Rotor Diameter (m)	1.12
Net Weight (Kg)	7
Cut-in Wind Speed (m/s)	2.1
Rated Power (W)	250
Max Power (W)	400
Pole Dimensions (mm)	(Inner Diameter) 41
Package Weight (Kg)	10

An Automatic Braking Systems Based on FLC

Figure 3 shows the block diagram of the proposed automatic braking systems. The voltage sensor uses to sense generator voltage then compared to the setpoint voltage to determine the error and delta error. Both become the input of the Arduino UNO, which will be processed based on the fuzzy algorithm. The Arduino UNO output is connected to the MOSFET to determine the on/off switching period automatic braking systems based on the PWM signal.

Fuzzy logic is chosen for the proposed automatic braking systems since this algorithm categorizes as an intelligent method that transfers human intelligence logic into computers or microcontrollers devices [12]. In addition, this algorithm has been proven to optimize control systems in various fields [13]–[16].

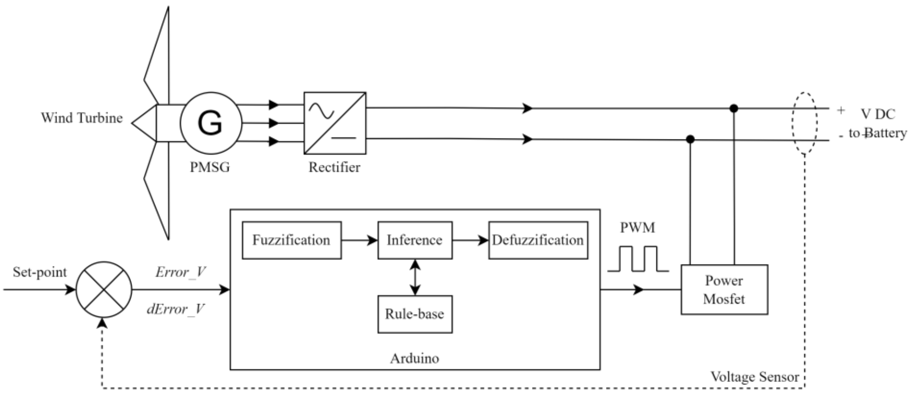

Figure 3. Block Diagram of Proposed Automatic Braking Systems

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Compared to classical logic, fuzzy logic has a value between 0 to 1, not only if-then like Boolean logic [17]. Therefore, this algorithm is suitable for modeling various systems and solving non-linear mapping problems.

The fuzzy logic design process in this study is carried out by Fuzzy Inference System (FIS) ToolBox on MATLAB/Simulink software, wherein the approach method used is the Mamdani method. The Mamdani method's three steps consist of a fuzzification process, a rule-based inference process, and a defuzzification process [18], as shown in Figure 4.

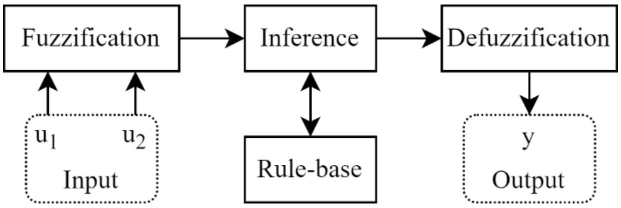

Figure 4. Diagram Block of Fuzzy Logic Process

Fuzzification Process

This step is used to determine the degree of the input variable's membership to result in the output of an if-then rule [19], which calculates the area under the fuzzy set curve. In the Mamdani method, both input (antecedent/premise) and consequent output variables/conclusions are divided into one or more fuzzy sets. Therefore, the fuzzification process aims to obtain input and output membership functions, respectively. The inputs consist of voltage error (*Error_V*) and delta error (*dError_V*) values from the voltage sensor reading, while the fuzzy output is the PWM value.

The membership function of *Error_V* variable input is the difference between the voltage sensor reading and the set-point values. Figure 5 shows the membership function of the *Error_V* variable with set negative (*N*) and positive (*P*) used the trapezoidal membership function trapmf type with a range *of* $N \geq -5$, $N \leq 0$ *and* $P \geq 0$, $P \leq 5$. Meanwhile, the set zero (*Z*) used a triangular membership function trimf type with a value range of $Z \geq -3$, $Z \leq 3$. The membership function of *Error_V* is shown in Equation (1) to (3).

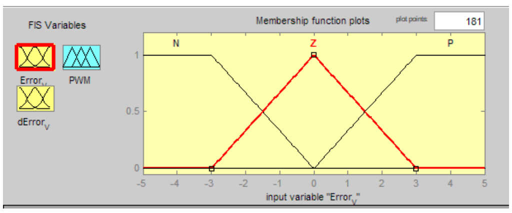

Figure 5. Membership Function of *Error_V*

$$\mu f([x], N) = \begin{cases} 0; & x \leq a \text{ or } x \geq c \\ 1; & a \leq x \leq b \\ \dfrac{c-x}{c-b}; & b \leq x \leq c \end{cases} \quad (1)$$

$$\mu f([x], Z) = \begin{cases} 0; & x \leq b \text{ or } x \geq d \\ \dfrac{x-c}{b-c} & b \leq x \leq c \\ \dfrac{d-x}{d-c}; & c \leq x \leq d \end{cases} \quad (2)$$

$$\mu f([x], P) = \begin{cases} 0; & x \leq c \text{ or } x \geq e \\ 1; & d \leq x \leq e \\ \dfrac{x-c}{d-c}; & c \leq x \leq d \end{cases} \quad (3)$$

Furthermore, the *dError_V* variable is a difference between current and previous errors. Figure 6 shows the membership function of the *dError_V* variable with set *N* and *P* used the trapmf type with a value range of $N \geq -5$, $N \leq 0$ *and* $P \geq 0$, $P \leq 5$. Meanwhile, the set *Z* used a trimf type with a value range of $Z \geq -3$, $Z \leq 3$. Equation (4) to (6) shows the membership function of the *dError_V* variable.

$$\mu f([x], dN) = \begin{cases} 0; & x \leq a \text{ or } x \geq c \\ 1; & a \leq x \leq b \\ \dfrac{c-x}{c-b} & b \leq x \leq c \end{cases} \quad (4)$$

$$\mu f([x], dZ) = \begin{cases} 0; & x \leq b \text{ or } x \geq d \\ \dfrac{x-b}{c-b}; & b \leq x \leq c \\ \dfrac{d-x}{d-c}; & c \leq x \leq d \end{cases} \quad (5)$$

$$\mu f([x], dP) = \begin{cases} 0; & x \leq c \text{ or } x \geq e \\ 1; & d \leq x \leq e \\ \dfrac{x-c}{d-c}; & c \leq x \leq d \end{cases} \quad (6)$$

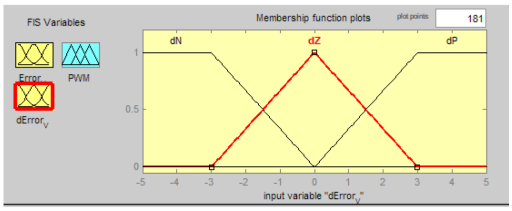

Figure 6. Membership Function of *dError_V*

Finally, determining the membership function of PWM variable output. The PWM variable is an 8-bit modulated pulse width value, such as 0-255. Figure 7 shows the membership function of the PWM variable with set low (*L*) and moderate (*S*) used a trimf type with a range of $L \geq 0$, $L \leq 10$, *and* $S \geq 0$, $S \leq 20$. Meanwhile, set fast (*C*) used the trapmf type with a range of $C \geq -10$, $C \leq 100$. The membership function of the PWM variable is shown in Equation (7) to (9).

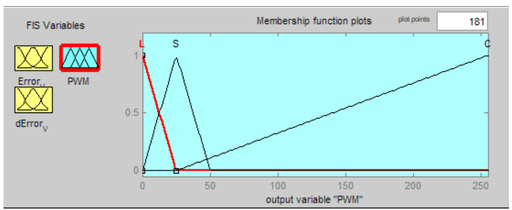

Figure 6. Membership Function of PWM

$$\mu f([x], L) = \begin{cases} 0; & x \leq a \text{ or } x \geq b \\ \dfrac{b-x}{b-a}; & a \leq x \leq b \end{cases} \quad (7)$$

$$\mu f([x], S) = \begin{cases} 0; & x \leq a \text{ or } x \geq c \\ \dfrac{x-a}{b-a}; & a \leq x \leq b \\ \dfrac{c-x}{c-b}; & b \leq x \leq c \end{cases} \quad (8)$$

$$\mu f([x], C) = \begin{cases} 0; & x \leq b \text{ or } x \geq d \\ \dfrac{x-b}{d-b}; & b \leq x \leq d \end{cases} \quad (9)$$

Rule-Based Inference Process

The next step is the inferencing process for compiling fuzzy rules, which state the relationship between input and output variables [20]. The Mamdani method is employed to determine these variables' relationships. Table 2 shows the rule base created for this system which applied the implication function, OR (max value) and AND (min value). This function is used to obtain the output condition consisting of the if-then rule based on the degree of truth of the antecedent.

Table 2. Systems Design of Rule Base

dError*/*Error	**Negative (*N*)**	**Zero (*Z*)**	**Positive (*P*)**
dNegative (*dN*)	Fast (*C*)	Fast (*C*)	Slow (*L*)
dZero (*dZ*)	Fast (*C*)	Moderate (*S*)	Slow (*L*)
dPositive (*dP*)	Fast (*C*)	Slow (*L*)	Slow (*L*)

Based on Table 2, the next step defines the if-then rule using the Rule Editor in MATLAB. As a result, nine rules are obtained, as shown in Table 3. Furthermore, the aggregation function is the process is conducted to combine all if-then rules into a single fuzzy set. When there is more than one consequent part, it is accomplished separately for each output variable rule. Wherein there are three methods used to carry out fuzzy system inference: max, additive, and probabilistic OR.

Table 3. Rule Based The Proposed Systems

Rules		**Conditions**
Rule-1	:	If (*Error_V* is *N*) and (*dError_V* is *dN*) then (PWM is *C*)
Rule-2	:	If (*Error_V* is *N*) and (*dError_V* is *dZ*) then (PWM is *C*)
Rule-3	:	If (*Error_V* is *N*) and (*dError_V* is *dP*) then (PWM is *C*)
Rule-4	:	If (*Error_V* is *Z*) and (*dError_V* is *dN*) then (PWM is *C*)
Rule-5	:	If (*Error_V* is *Z*) and (*dError_V* is *dZ*) then (PWM is *S*)
Rule-6	:	If (*Error_V* is *Z*) and (*dError_V* is *dP*) then (PWM is *L*)
Rule-7	:	If (*Error_V* is *P*) and (*dError_V* is *dN*) then (PWM is *L*)
Rule-8	:	If (*Error_V* is *P*) and (*dError_V* is *dZ*) then (PWM is *L*)
Rule-9		If (*Error_V* is *P*) and (*dError_V* is dP) then (PWM is *L*)

Defuzzification Process

The last step fuzzy logic design process is defuzzification, which reaffirms the obtained fuzzy set into a crisp value [21]. During the inference engine rules evaluation, the Mamdani method used the min function, while the inter-rule composition employed the max function to generate a new fuzzy set. Various defuzzification methods can be realized in the Mamdani method, consisting of center of area (COA), bisector of area (BOA), mean of maximum (MOM), largest of maximum (LOM), and smallest of maximum (SOM) [22]. The process used in the study is the MOM method, which calculates the average value of the maximum output membership degree (*Z*) by Equation (10) and can be illustrated in Figure 7.

$$Z = \frac{(a+b)}{2} \tag{10}$$

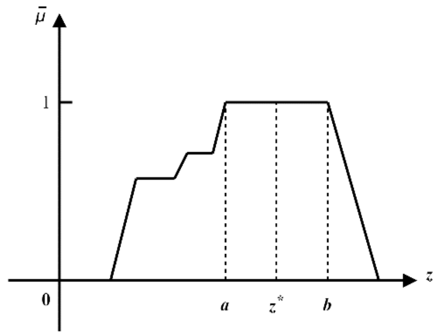

Figure 7. Mean of Maximum (MOM) Defuzzification Method

RESULTS AND DISCUSSION

The first result is testing the voltage sensor reading used in the proposed systems to investigate its accuracy. Before implementing it in the turbine generator PLTH Bayu Baru which is conducted by varying DC voltage using a DC/DC step-down. Table 4 shows the voltage sensor testing. The highest error has occurred under the generator voltage of about 12V. In contrast, the lowest error has occurred near the generator voltage. By testing nine times with varying voltage, the average error is 2.88%.

Table 4. Voltage Sensor Testing

No	**Voltage Variation (V)**	**Sensor Voltage Reading (V)**	***Error* (%)**
1	9.00	9.33	3.67
2	9.50	9.84	3.58
3	10.00	10.30	3.00
4	10.50	10.80	2.86
5	11.00	11.30	2.72
6	11.50	11.80	2.61
7	12.00	12.30	2.50
8	12.50	12.80	2.40
9	13.00	13.40	3.08

Furthermore, the implementation of the proposed automatic wind turbine braking system for PLTH Bayu Baru is illustrated in Figures 8, which the proposed system functions to replace the manual switch in exisisting systems.

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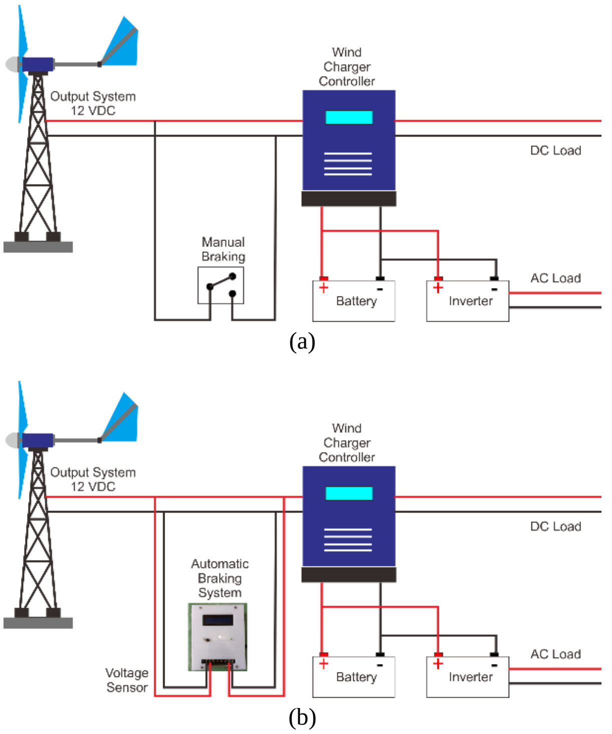

Figure 8. Wind Turbine in PLTH Bayu Baru: (a) Existing System with Manual Braking, and (b) Implementing of the Proposed Systems

The generator generates electricity from the turbine blade's rotation when the wind turbine rotates. The generator with a 12VDC/400W will produce DC electricity which connects to the battery. The wind speed sample measurements using an anemometer obtain the speed between 3.7 m/s to 7.2 m/s with the turbine rotation between 112 rpm and 171 rpm. The average generator voltage generated is 13.8V, exceeding its standard voltage during the testing process. Afterward, by applying the proposed braking systems, the result testing is shown in Table 4.

Table 4. The Automatic Braking Proposed System Test Results

No	Voltage (V)	*Error_V*	*dError_V*	PWM
1	5.44	8.28	7.50	0
2	13.06	8.66	-7	87.09
3	5.66	8.06	7.40	0
4	8.74	4.98	-3	0
5	12.55	1.17	-3	0
6	13.40	0.51	0	47.40
7	7.20	6.52	6.00	0
8	12.33	1.39	0	0
9	13.16	0.56	0	52.49
10	4.37	9.35	8.70	0

The setpoint voltage in the proposed systems is 13.5V to ensure the generator voltage results are not more than 13.8V. Also, this value is used to discover the braking effect which occurs during system testing, wherein it generates a fluctuating voltage as shown in Figure 9 due to reaching setpoint voltage. The proposed braking systems are active by providing a PWM signal involved trigger voltage above 5V for the MOSFET gate, leading to a smooth braking system. Whereas, when the generator voltage is less than the setpoint voltage, the proposed braking systems do not act.

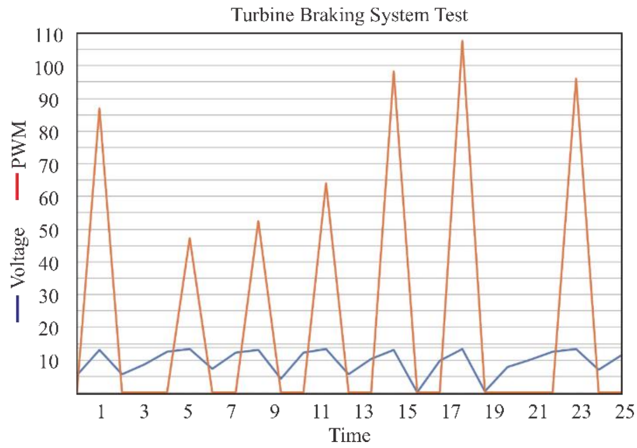

Figure 9. The Test Resulting of The Automatic Braking Proposed Systems

The proposed systems work correctly and are suitable for replacing manual braking in existing systems PLTH Bayu Baru considering the testing result conducted. By utilizing FLC, this system has been adopted an intelligent method, wherein similar works have also been conducted involving other methods. In [23] proposed automatic brake small-scale wind turbine by applying Proportional-Derivative Particle Swam Optimization (PD-PSO). The rotation speed of the wind turbine detection employs a rotary encoder, in which the output signal is sent to the microcontroller. The digital computation is conducted based on the algorithm used, and its output is used to decrease the wind turbine rotational speed using a servo motor. Due to the algorithm used being a modification, it is impacted the computation speed and needs capable devices to handle it.

Furthermore, with the same algorithm used in this study, the proposed braking systems are introduced by [24], which combines FLC systems with DC chopper for wind turbine generators. Meanwhile, the aerodynamic power control, including automatic braking systems introduced in [25], wherein FLC is applied for the pitch of the blades angle control to keep the voltage standard value and power output of the generator transmitting to the dc bus. Therefore, the FLC method is valid to implement in the automatic braking proposed by this study, which is applied to PLTH Bayu Biru. It only needs to be appropriated based on wind turbine generator objects respectively.

CONCLUSION

The automatic braking systems based on FLC are proposed in this study to replace the manual braking existing in wind turbine generator PLTH Bayu Baru. From the testing, the proposed systems can work properly when the voltage generator is produced over the setpoint voltage 13.5V. The wind turbine generator will be brake by MOSFET triggered 5V voltage from the driver circuit also microcontroller. By applying the fuzzy logic algorithm, this proposed system prevents the possible problems caused by excessive wind turbine rotation.

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