

Certain Investigations on Modified Fuzzy-based Adaptive Controller for Mitigating the Deviations in Wind System

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Abstract—In the realm of wind energy systems, the quest for optimal control strategies has led to the exploration of innovative approaches. This study delves into the realm of adaptive control, specifically focusing on a Modified Fuzzy-Based Adaptive Controller designed to mitigate deviations in wind systems. This controller, a product of meticulous investigation, harnesses the power of fuzzy logic with strategic modifications to enhance its adaptability. The proposed controller exhibits a remarkable ability to dynamically adjust its parameters, ensuring optimal performance across diverse operating conditions. Through rigorous experimentation and analysis, the controller's efficacy in mitigating deviations in wind systems has been established, marking a significant advancement in the quest for robust and efficient control strategies. Renewable energy is an ever-changing field, and the Modified Fuzzy-Based Adaptive Controller is a significant advancement. This controller has the ability to adjust parameters dynamically and mitigate deviations in wind systems, which improves the efficiency of wind energy systems and contributes to the broader field of adaptive control. As innovation continues to shape the future of sustainable energy, this controller serves as a testament to the relentless pursuit of a more resilient and environmentally conscious world.

Index Terms— WECS, Fuzzy Logic, PMSG, Fuzzy based Adaptive Controller.

I. INTRODUCTION

In the dynamic arena of renewable energy, pursuing optimal control strategies for wind energy systems has fueled a continuous exploration of inventive methodologies. This research narrative unfolds with a spotlight on adaptive control, honing in on a pioneering solution—the Modified Fuzzy-Based Adaptive Controller. Crafted through a systematic investigative process, this controller emerges as a transformative stride in addressing and rectifying deviations within wind systems. At its conceptual core lies the strategic amalgamation of fuzzy logic, enriched with nuanced modifications that amplify its versatility. This introduction lays the groundwork for an exploration into the intricacies of this controller, spotlighting its prowess in dynamically adapting parameters. The study showcases the effectiveness of the controller in reducing deviations and optimizing wind energy systems. It advances the field of adaptive control and positions the Modified Fuzzy-Based Adaptive Controller as a key player. This introduction invites readers to a realm where innovation and environmental consciousness come together, guided by the transformative power of this cutting-edge controller. An effective method to maximize the acquisition of the Maximum Power Point in a direct-driven Permanent

Magnet Synchronous Generator (PMSG) based wind power conversion system is to use a Fuzzy Logic Controller (FLC). The FLC method effectively observes the position information of the PMSG, enhancing the system's anti-disturbance capabilities in a linear state. To enhance energy conversion efficiency and optimise wind energy utilisation, sophisticated control algorithms are necessary due to obstacles posed by both internal and external disturbances. The proposed FLC method, combined with sliding mode control[3], proves to be a simple, low-cost, and reliable solution, exhibiting superior performance in various operational[1] circumstances and effectively recognizing rotor positions under dynamic conditions.

II. WIND TURBINE DISTURBANCES AND CONTROL STRATEGIES

1. External disturbances :
 - i. Wind Variability: Changes in wind speed and direction can lead to fluctuations in power output and mechanical loads on the turbine components.
 - ii. Temperature Changes: Extreme temperatures can impact the performance of materials and lubricants, affecting the overall efficiency and lifespan of the turbine.
 - iii. Lightning Strikes: Lightning strikes have the potential to harm vital components such as control systems and blades of wind turbines.
 - iv. Bird Strikes: Birds colliding with turbine blades can result in damage to the blades and pose environmental concerns.
2. Internal disturbances:
 - i. Mechanical Wear and Tear: Friction, wear, and fatigue in mechanical components like bearings and gears can lead to internal disturbances, affecting the turbine's overall performance.
 - ii. Electrical Issues: Problems within the electrical systems, such as faults in wiring or components, can cause disruptions in power generation and transmission.
 - iii. Sensor Malfunctions: Faulty sensors or inaccuracies in sensor readings may introduce disturbances in the control system, impacting the turbine's ability to respond accurately to changing conditions.
 - iv. Vibration and Resonance: Excessive vibrations or resonance within the turbine structure can lead to dynamic instabilities, affecting both mechanical and electrical components.

III. TYPES OF WIND TURBINE CONTROLLING METHODS

There are several types of wind mill (wind turbine) controlling methods, each designed to optimize the performance and efficiency of wind turbines under varying conditions[9]. Some of the common windmill controlling methods include:

- Pitch Control: Using this technology, the wind turbine blades' pitch angle is adjusted (Fig. 1 displays the pitch angle controller block diagram) to maximize aerodynamic performance. Pitch control varies the amount of energy the turbine can extract from the wind based on load and wind speed.
- Active Stall Control: The purpose of the blades in active stall-controlled turbines is to stall at high wind speeds, lowering the angle of attack and regulating the power production. During high winds, this technique offers a passive means to reduce power.
- Yaw Control[2]: Yaw control is the process of changing the wind turbine's orientation to the direction of the wind. By yawing or rotating the nacelle, or turbine housing, towards the wind, the blades may be able to capture the greatest wind energy. To guarantee that the wind turbine is always oriented in the direction of the predominant wind, [7]yaw control is essential.
- Fuzzy Logic Control: Fuzzy control (Fig.1) utilizes linguistic variables and fuzzy logic to make control decisions based on imprecise or uncertain information. It provides adaptability and flexibility in handling nonlinear and uncertain wind turbine dynamics.

IV. MATHEMATICAL MODELLING OF WIND TURBINE

A wind turbine comprises a tower with multiple blades physically attached to an electric generator and a rotor fixed on a nacelle. The torque or power output of a wind turbine is influenced by several variables, including turbine Speed, rotor blade pitch angle, rotor blade tilt, turbine size and form, the area where the turbine's blades sweep, the wind's velocity.

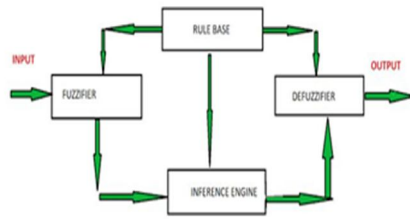


Figure 1. Fuzzy Logic

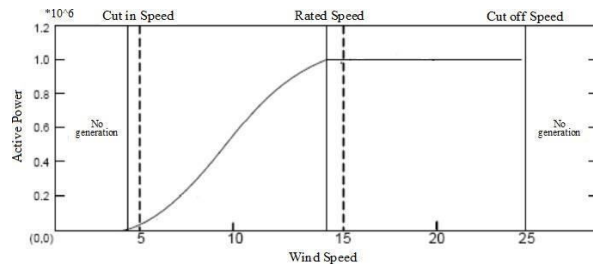


Figure 2. Typical turbine mechanical power vs. wind speed curve with stall and pitch control

When an object with mass "m" and velocity "v" is pushed from rest to a distance "s" under force "F" and constant acceleration "a," its kinetic energy (E) is equal to the work done (w) or $E = F \cdot s$.

$$F = m \cdot a$$

thus, the KE changes into

$$E = m \cdot a \cdot s$$

from the solid motion kinematics formula, $v^2 = u^2 + 2 \cdot a \cdot s$ where 'u' represents the object's starting velocity and $a = \frac{v^2 - u^2}{2 \cdot s}$. Knowing that object zero's starting velocity is $a = \frac{v^2}{2 \cdot s}$

$$E = 0.5 \cdot m \cdot v^2$$

The rate at which KE changes determines the wind's power, or "P."

$$P = \frac{dE}{dt} = 0.5 \times \frac{dm}{dt} \times v_w^2$$

Where $\frac{dm}{dt} = \rho \cdot A \cdot V_w$;

$$P = 0.5 \times \rho \times V_w^3$$

$$P_w = 0.5 \times \rho \times A \times V_w \times (V_u^2 - V_d^2)$$

Where V_d and V_w represent the upstream wind velocity in meters per second at the rotor blade entrance.

$$P_w = 0.5 \times \rho \times A \times (V_u^2 - V_d^2) \times \left(\frac{V_u + V_d}{2} \right)$$

$$P_w = 0.5 \times \left[\rho \times A \left\{ \frac{V_u}{2} (V_u^2 - V_d^2) + \frac{V_d}{2} (V_u^2 - V_d^2) \right\} \right]$$

$$P_w = 0.5 \times \rho \times A \times V_u^3 \times C_p$$

$$\text{here, } C_p = \frac{1 - \frac{V_d^2}{V_u^2} + \frac{V_d}{V_u} - \frac{V_d^3}{V_u^3}}{2}$$

The term for C_p is the percentage of upstream wind power that the rotor blades catch. The power coefficient's value fluctuates. Define λ as the ratio between the turbine's upstream (V_u) and downstream (V_d) wind speeds.

$$\lambda = V_d / V_u = 1 / \text{wind speed} / \text{blade tip speed}$$

- The wind-turbine tip speed ratio is denoted by λ .
- blade tip Speed = angular Speed of turbine (ω) $\times$ R / wind speed
- Where 'R' is the radius of the turbine and ' ω ' is measured in radian per second

$$C_p = \frac{(1 + \lambda)(1 - \lambda^2)}{2}$$

Differentiate C_p with respect to λ and set it to zero to find the value of λ that makes C_p maximum. We obtain $\lambda = 1/3$ or $\lambda = -1$.

With a specific value of $\lambda = 1/3$, the corresponding coefficient of power (C_p) reaches its maximum, attaining a value of 16/27. According to the Betz limit, this implies that no wind turbine has the capability to convert more than 16/27 (equivalent to 59.3%) of the kinetic energy from the wind into mechanical energy. Therefore, the maximum achievable C_p , as per Betz limit, is 0.59.

$P = PRT$, R represents the gas in this instance. Constant at $T = 60^\circ\text{F}$, density $\rho = 1.225 \text{ kg/m}^3$, and atmospheric pressure, $P_{\text{atm}} = 14.7 \text{ psi}$. Both pressure and temperature fluctuate with height.

$$\rho = \rho_0 \times e^{\frac{-0.297}{3048} Hm}$$

where Hm is the site's height in meters. The air density corrections might be significant at high heights. Analysis of power coefficient (power vs. wind speed curve is shown in Fig.4

The parameters needed for a wind turbine to produce electricity are found in equation $P_w = 0.5 \times \rho \times A \times V_w^3 \times C_p$. This function is nonlinear and is dependent on wind speed at which the turbine is running. Its values are specific to each kind of turbine. Lookup tables are provided by each turbine maker for C_operational purposes. The function of C_p depends on the blade pitch angle θ in degrees and the tip speed ratio.

$$C_p(\lambda, \theta) = C_1(C_2 \frac{1}{\beta} - C_3 * \beta * \theta - C_4 * \theta - C_5) e^{-C_6 * \frac{1}{\beta}}$$

where the turbine type affects the values of coefficients C_1 through C_6 . The definition of θ is the angle formed between the plane of rotation and the chord of the blade cross section ($C_1 = 0.5$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 0$, $C_5 = 5$, $C_6 = 21$). The definition of β is $\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} + \frac{0.035}{1 + \theta^3}$.

Relation for C_p ; $C_p = 0.5(\lambda - 0.022 * \theta^2 - 5.6)e^{-0.17\lambda}$

Where W_b is the turbine's angular speed, V_w is its velocity in miles per hour, and λ is the turbine's tip speed ratio, which is described as $\lambda = (V_w \text{ (mph)}) / (W_b \text{ (rad/s)} \wedge (-1))$.

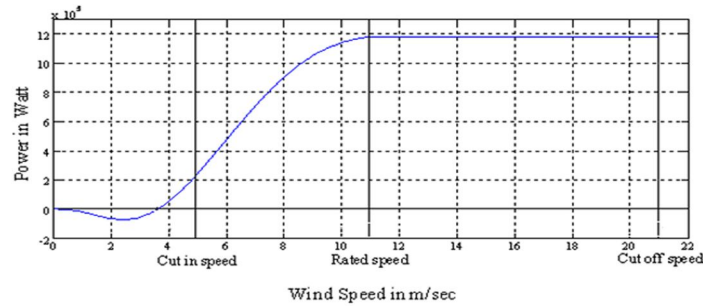


Figure3. Power vs. Wind Speed

V. PMSG MODELLING

[6],[9] Permanent Magnet Synchronous Machines operate either in engine or generator mode. The mechanical force indicator (negative for generator mode, positive for engine mode) controls the activity's course. This particular kind of electric generator is employed in wind turbines among other things. In order to comprehend and forecast a PMSG's behaviour under various operating situations, modelling entails developing mathematical representations and simulations (a Simulink model is displayed in Figure 5).

A. Electrical model

Modelling a PMSG electrically involves representing the Electrical relationships within the generator.

Stator voltage Equations: It will describe the relation between stator phase voltages, currents and generator parameters. This can be represented in the d_q frame 'd' represents the direct axis aligned with the magnetic field and 'q' represents the quadratic axis perpendicular to the magnetic field.

d-axis:

$$V_{sd} = e_s \times I_{sd} - L_d \frac{dI_{sd}}{dt} + \omega \times L_q \times I_{sq}$$

q-axis:

$$V_{sq} = e_s \times I_{sq} - L_q \frac{dI_{sq}}{dt} + \omega \times L_d \times I_{sd}$$

✓ Basic EMF equations:

d-axis:

$$E_d = \omega \times \lambda_m$$

q-axis:

$$E_q = \omega \times \lambda_m$$

E_d and E_q are basic emf voltages in d and q axes respectively and λ_m is the magnetic flux linkage.

✓ Stator current equations:

$$\text{d-axis: } I_{sd} = \frac{V_{sd} - E_d}{R_s}, \quad \text{q-axis: } I_{sq} = \frac{V_{sq} - E_q}{R_s}$$

✓ Rotor current equations:

PMSG has a rotor with permanent magnets so $I_{rd}=0$ and $I_{rq}=0$. Flux linkage equations: $\lambda_m = L_d \times I_{sd} + L_q \times I_{sq}$

$$T_e = 1.5[\lambda_{iq} + (L_d - L_q)]$$

Where (the stator is the reference point for all quantities in the rotor reference frame) L_q , L_d axis inductances for q and d. R is the stator windings' resistance (i_q), it is the q and axis currents. V_q , V_d = q and d axis voltages; ω = rotor angle velocity.

B. Mechanical Model

It explains the connection between the electromagnetic torque, mechanical load torque, and generator mechanical dynamics.

$$J \times \frac{dw}{dt} = T_m - T_l$$

Where:

- 'J' is MoI of the generator and connected mechanical system, it represent the framework resistance to change angular velocity.
- 'w' is angular velocity (rotor speed) of generator.
- ' T_m ' is electromagnetic torque generated by PMSG.
' T_l ' is mechanical Load torque applied to generator.

C. Control System Model

Control system modelling for Permanent magnet Synchronous Generator involves creating equations that describe the control strategy used to regulate the generator's electrical output. This includes controlling the generators rotor speed to optimize power output especially in wind turbines.

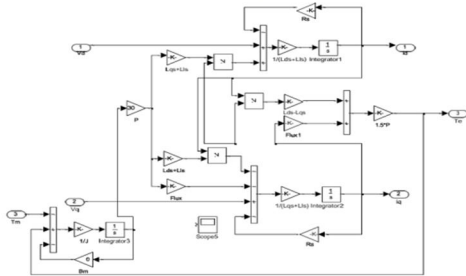


Figure 4. Simulink model of PMSG

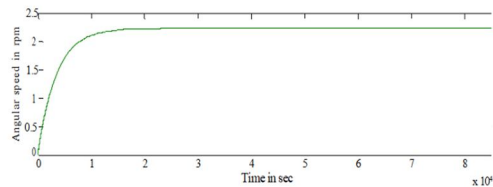


Figure 5. Rotor Angular Speed in rpm

PMSG Angular Speed and Torque

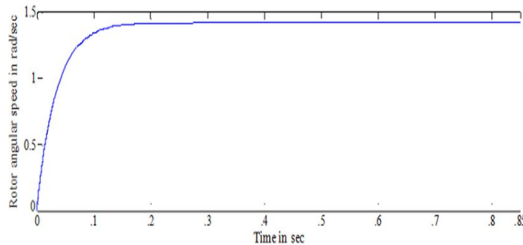


Figure 6. Rotor Angular Speed in rad/sec

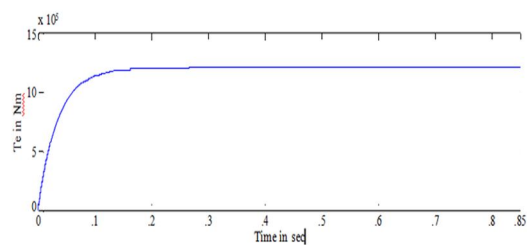


Figure 7. Electromagnetic Torque

VI. FUZZY LOGIC CONTROLLER

A Fuzzy Logic Controller (FLC)[5] is a sophisticated control is a frame work that operates on the principles of fuzzy logic, a mathematical framework designed to handle uncertainty and imprecision in information. In contrast to classical control systems, which rely on precise mathematical models, FLCs are well-suited for applications where the available data is vague or ambiguous. At its core, a FLC consists of several interconnected components that work together to make decisions and regulate processes. The foundational concept in fuzzy logic [7]is the expansion of traditional set theory to fuzzy sets, where elements can have degrees of membership ranging from 0 to 1. Linguistic variables, such as "low," "medium," and "high," are employed to represent qualitative terms, providing a more intuitive understanding of system behaviour.

Fuzzification is the initial step, converting crisp input values into fuzzy values by assigning membership grades based on predefined fuzzy sets. The rule base, a collection of expert-defined IF-THEN rules, establishes the relationship between fuzzy input conditions and fuzzy output variables. An inference engine evaluates these rules, combining them to generate a fuzzy output. The aggregation process considers all applicable rules and merges their results, leading to a comprehensive fuzzy output.

The final step, defuzzification, transforms the fuzzy output into a precise, actionable output for controlling the system. Fuzzy Logic Controllers[8] have found widespread applications in diverse fields, including industrial control systems, consumer electronics, and automotive systems. Their ability to model complex relationships without the need for exact mathematical equations makes them particularly valuable in scenarios where uncertainties prevail. In conclusion, [10]FLCs provide a robust framework for decision-making in dynamic environments characterized by imprecise information, making them a valuable tool in modern control engineering.

Fuzzy Rules

TABLE I. FUZZY RULES

s no	Description	Antecedent	Consequent	Weight	Connection
1	Error==NB & change.of.error==NB => output=NB (1)	[1,2]	1	1	1
2	Error==NB & change.of.error==NM => output=NB (1)	[1,3]	1	1	1
3	Error==NB & change.of.error==NS => output=NB (1)	[1,4]	1	1	1
4	Error==NB & change.of.error==ZE => output=NB (1)	[1,1]	1	1	1
5	Error==NB & change.of.error==PS => output=NM (1)	[1,5]	2	1	1
6	Error==NB & change.of.error==PM => output=NS (1)	[1,6]	3	1	1
7	Error==NB & change.of.error==PB => output=ZE (1)	[1,7]	4	1	1
8	Error==NM & change.of.error==NB => output=NB (1)	[2,2]	1	1	1
9	Error==NM & change.of.error==NM => output=NB (1)	[2,3]	1	1	1
10	Error==NM & change.of.error==NS => output=NB (1)	[2,4]	1	1	1
11	Error==NM & change.of.error==ZE => output=NM (1)	[2,1]	2	1	1
12	Error==NM & change.of.error==PS => output=NS (1)	[2,5]	3	1	1
13	Error==NM & change.of.error==PM => output=ZE (1)	[2,6]	4	1	1
14	Error==NM & change.of.error==PB => output=PS (1)	[2,7]	5	1	1
15	Error==NS & change.of.error==NB => output=NB (1)	[3,2]	1	1	1
16	Error==NS & change.of.error==NM => output=NM (1)	[3,3]	2	1	1
17	Error==NS & change.of.error==NS => output=NS (1)	[3,4]	3	1	1
18	Error==NS & change.of.error==ZE => output=NS (1)	[3,1]	3	1	1
19	Error==NS & change.of.error==PS => output=ZE (1)	[3,5]	4	1	1
20	Error==NS & change.of.error==PM => output=PS (1)	[3,6]	5	1	1
21	Error==NS & change.of.error==PB => output=PM (1)	[3,7]	6	1	1
22	Error==ZE & change.of.error==NB => output=NB (1)	[4,2]	1	1	1
23	Error==ZE & change.of.error==NM => output=NM (1)	[4,3]	2	1	1
24	Error==ZE & change.of.error==NS => output=NS (1)	[4,4]	3	1	1
25	Error==ZE & change.of.error==ZE => output=ZE (1)	[4,1]	4	1	1
26	Error==ZE & change.of.error==PS => output=PS (1)	[4,5]	5	1	1
27	Error==ZE & change.of.error==PM => output=PM (1)	[4,6]	6	1	1
28	Error==ZE & change.of.error==PB => output=PB (1)	[4,7]	7	1	1
29	Error==PS & change.of.error==NB => output=NM (1)	[5,2]	2	1	1
30	Error==PS & change.of.error==NM => output=NS (1)	[5,3]	3	1	1
31	Error==PS & change.of.error==NS => output=ZE (1)	[5,4]	4	1	1
32	Error==PS & change.of.error==ZE => output=PS (1)	[5,1]	5	1	1
33	Error==PS & change.of.error==PS => output=PS (1)	[5,5]	5	1	1
34	Error==PS & change.of.error==PM => output=PM (1)	[5,6]	6	1	1
35	Error==PS & change.of.error==PB => output=PB (1)	[5,7]	7	1	1
36	Error==PM & change.of.error==NB => output=NS (1)	[6,2]	3	1	1
37	Error==PM & change.of.error==NM => output=ZE (1)	[6,3]	4	1	1
38	Error==PM & change.of.error==NS => output=PS (1)	[6,4]	5	1	1
39	Error==PM & change.of.error==ZE => output=PM (1)	[6,1]	6	1	1
40	Error==PM & change.of.error==PS => output=PM (1)	[6,5]	6	1	1
41	Error==PM & change.of.error==PM => output=PB (1)	[6,6]	7	1	1
42	Error==PM & change.of.error==PB => output=PB (1)	[6,7]	7	1	1
43	Error==PB & change.of.error==NB => output=ZE (1)	[7,2]	4	1	1
44	Error==PB & change.of.error==NM => output=PS (1)	[7,3]	5	1	1
45	Error==PB & change.of.error==NS => output=PM (1)	[7,4]	6	1	1
46	Error==PB & change.of.error==ZE => output=PB (1)	[7,1]	7	1	1
47	Error==PB & change.of.error==PS => output=PB (1)	[7,5]	7	1	1
48	Error==PB & change.of.error==PM => output=PB (1)	[7,6]	7	1	1
49	Error==PB & change.of.error==PB => output=PB (1)	[7,7]	7	1	1

Where NB stands for Negative Big. Negative Medium is NM. Negative Small is NS. Positive Small is PS. PM stands for Positive Medium. Positive Big is PB. Zero is ZE.

VII. BLOCK DIAGRAM AND SIMULATION RESULTS

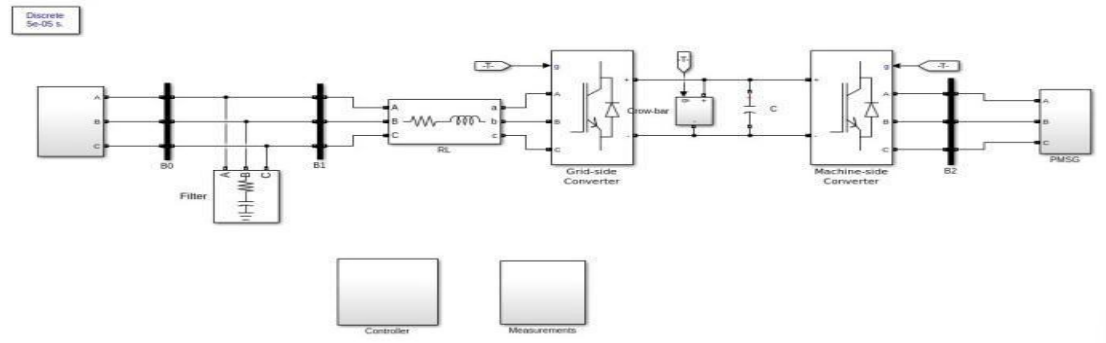


Figure 8. Fuzzy Simulink

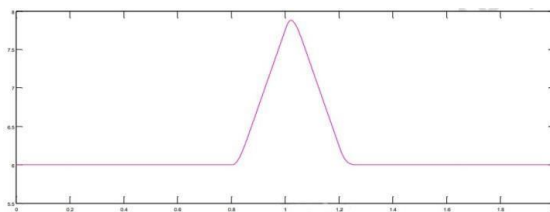


Figure 9. Wind Speeds Vw

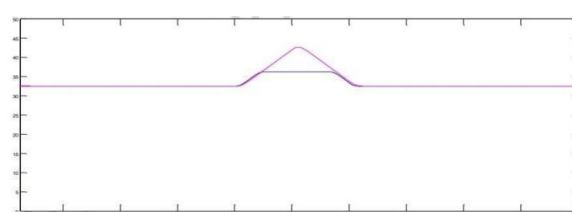


Figure 10. Generator speed

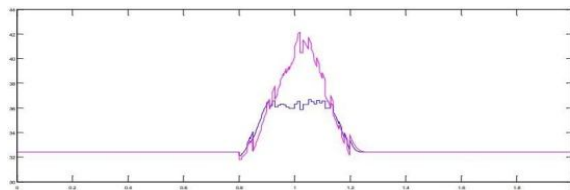


Figure 11. Generator speed with penetrations

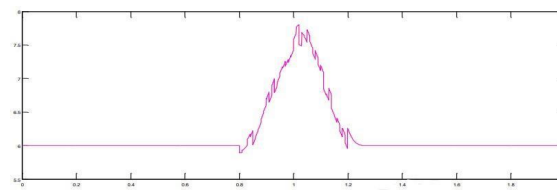


Figure 12. Wind Speeds

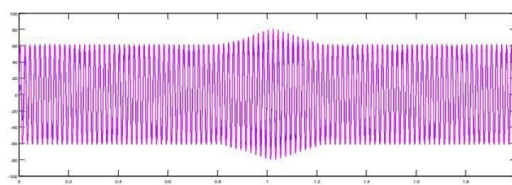


Figure 13. Back EMF

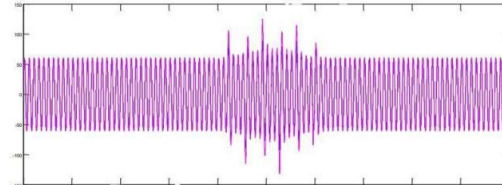


Figure 14. Back EMF with fuzzy

VIII. CONCLUSION

In conclusion, the study delving into the realm of adaptive control within wind energy systems has unveiled a groundbreaking achievement in the form of the Modified Fuzzy-Based Adaptive Controller. This innovative controller, born out of rigorous investigation and strategic enhancements, exhibits unparalleled adaptability through the integration of fuzzy logic. Its unique ability to dynamically adjust parameters ensures optimal performance across a spectrum of operating conditions, signifying a monumental advancement in [4] control strategy design.

Through comprehensive experimentation and analysis, the controller's efficacy in mitigating deviations within wind systems has been robustly established[6]. This study provides concrete proof of the performance of the Modified Fuzzy-Based Adaptive Controller to the continuously expanding corpus of knowledge in adaptive control and renewable energy. The[5] controller's revolutionary potential shines as a light of progress in the

never-ending search of a resilient and ecologically conscious world, especially as the need for sustainable energy grows. The synergy of innovation and environmental consciousness embodied in this controller underscores its potential to shape the future trajectory of renewable energy systems. As we navigate the challenges of a changing climate, the Modified Fuzzy-Based Adaptive Controller stands poised as a beacon of hope, guiding the way towards more efficient, adaptable, and sustainable wind energy systems.

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