Innovative MPPT Tracking Methods for Combined Wind and Photovoltaic Energy System

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ABSTRACT

Traditional methods used to track the maximum power point in wind energy conversion systems (WECS) face several challenges. One of the most widely used techniques is the perturb and observe (P&O) algorithm, which monitors and records the highest possible power point. However, a major limitation of this algorithm is the difficulty in selecting an optimal step size. To address this issue, this study proposes a novel approach that integrates fuzzy logic control with the trapezoidal rule. The proposed method is compared with two existing techniques: the trapezoidal rule-based P&O (TRPO) algorithm and the conventional P&O method. MATLAB/Simulink simulations are used to evaluate the performance of all three algorithms under randomly varying wind speeds. The results demonstrate that the proposed approach significantly reduces power oscillations while enhancing DC output current, voltage, and power. Additionally, this study extends the methodology by incorporating a wind-solar hybrid system with an artificial neural network (ANN) model, further improving the efficiency and stability of renewable energy generation.

I. Overview

The global demand for energy has increased significantly due to rapid industrial growth, rising living standards, and population expansion. This surge in energy consumption has led to the depletion of conventional resources such as coal, gas, and oil. To address this issue and promote a sustainable future, renewable energy sources have gained popularity due to their environmental benefits and ability to meet energy demands. Among these, wind energy stands out as a clean and efficient source of power generation [1].

A Wind Energy Conversion System (WECS) is designed to harness wind power and convert it into electrical energy using power conversion equipment and wind turbines (WT). However, wind is an inherently fluctuating resource, making it challenging to extract maximum power efficiently. The primary role of a wind turbine is to capture wind energy and convert it into mechanical energy, which is then transformed into electrical power through a generator stage, as illustrated in Figure 1.

A. Wind Turbine Generators

Different types of generators are used in WECS, each with its advantages and drawbacks:

Squirrel Cage Induction Generator (SCIG):

Offers high reliability, low complexity, and cost-effectiveness.

However, it requires external excitation and has lower efficiency.

Doubly Fed Induction Generator (DFIG):

Works efficiently with partial-scale power converters, making it a cost-effective alternative to SCIG.

However, it requires a multi-stage gearbox and excitation system, increasing complexity [2, 3, 4].

Permanent Magnet Synchronous Generator (PMSG):

Self-excited, highly reliable, and cost-effective, making it a widely preferred choice [5, 6].

Table 1 provides a list of abbreviations and nomenclature used in this study.

B. Maximum Power Point Tracking (MPPT) in WECS

Due to wind speed variations, the power generated by a wind turbine fluctuates. Maximum Power Point Tracking (MPPT) techniques are employed to optimize power extraction under varying wind conditions. MPPT strategies fall into three categories [10]:

WT Parameter-Based Methods:

Require knowledge of wind turbine characteristics.

Examples: Tip Speed Ratio (TSR) and Optimal Torque Control (OTC) methods [11, 12, 13].

Sensor less Methods:

Do not require wind speed estimation or turbine characteristics.

Example: Perturb and Observe (P&O) algorithm [14].

Hybrid Methods:
Combine features of both approaches to improve tracking efficiency [10, 22, 23].
Among traditional MPPT techniques, the P&O algorithm is widely used due to its simplicity and lack of reliance on wind speed sensors. However, it has a key limitation—choosing the appropriate step size:
Large step sizes enable faster convergence to the Maximum Power Point (MPP) but cause power oscillations.
Small step sizes result in slow or incomplete convergence.

C. Advancements in MPPT Techniques
To overcome P&O limitations, researchers have explored hybrid and intelligent control approaches:
Modified P&O (MPO): Integrates with other methods like Power Signal Feedback (PSF) [24], Optimal Relation-Based (ORB) MPPT [25], and adaptive step-size approaches [26, 27, 28].
Fuzzy Logic Control (FLC): Enhances MPPT by making dynamic adjustments based on input variations [31, 32, 33, 34, 35, 36].
Artificial Neural Networks (ANN) & Metaheuristic Optimization: Applied in MPPT methods but have higher computational complexity and implementation costs [38, 39, 40].

D. Proposed Hybrid MPPT Approach
To address the limitations of traditional P&O and improve MPPT efficiency, this study integrates Fuzzy Logic Control (FLC) with the Trapezoidal Rule. The proposed technique operates as follows:
Trapezoidal Rule: Extracts maximum power and voltage values from rectified current and voltage.
FLC Implementation: Determines the duty cycle for tracking the MPP more effectively than standard P&O.

II. CONNECTED IDEAS
Figure 1 displays the wind power system's block diagram depiction. According to the Betz limit, only 59% of the energy that the wind possesses is harvested by the WT, which collects the power present in the wind, as seen in Figure 1. Equation (1) provides Pm, the mechanical power that is extracted from WT. The expression (2) gives the pair, or the power contained in the air, where ρ is the air density, V is the wind velocity in m/s, and A is the swept area covered by the turbine blades, expressed in m2.
Expression 3 gives the radius as R. Cp, the power coefficient, the angular velocity in rad/sec as ω, and the TSR as λ.

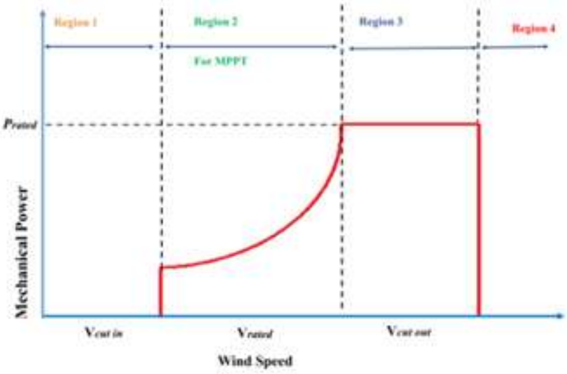

FIGURE 2. WECS operating regions [44].

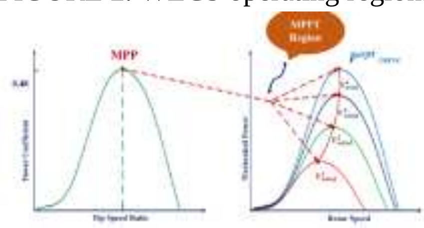

FIGURE 3. WT characteristics for λ opt and Cpopt . [44].

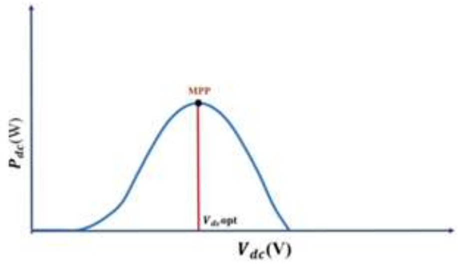

FIGURE 4. Relation between Vdc and Pdc.

The pair represents the contained power in the wind and the power absorbed, and the value shown in expression (4) is limited below 59%. by the wind turbine WTis. Equations 1, 2, 3, and 4 can be found in [26]. The generator stage receives input from the WT, which makes it easier to transform mechanical energy into electrical energy. The three-phase rectifier receives the generator's three-phase feed in order to convert DC. The MPPT algorithm regulates the DC-DC boost conversion, which is facilitated by the boost converter stage. The pulse width modulation (PWM) generator receives the duty cycle produced by the used algorithm and uses it to regulate the switching element, increasing the voltage and, consequently, the power. The several WECS output power zones are displayed in Figure 2. The first area shows the area where the WT is unable to generate any electricity due to of the wind's extremely slow speed. When it comes to the control element of getting the most power out of the

WECS, the area between the cutin and the rated wind speed is crucial. Since the wind speed in the third region falls between the rated and cutout levels, the system is protected. The area with wind speeds greater than the cutout values is represented by the fourth and final region.

$$P_m = \frac{1}{2}\rho A V^3 C_p(\lambda, \beta) \quad (1)$$

$$pair = \frac{1}{2}\rho A V^3 \quad (2)$$

$$\lambda = \frac{R*\omega}{V} \quad (3)$$

$$C_p = \frac{P_{windturbine}}{pair} \quad (4)$$

The second working region, where the MPPT approach is used to extract the most power from WECS, is the primary focus of this work. The MPPT idea for WECS is shown in Figure 3 quite well. Maximum power can be extracted when the WECS operation occurs at the optimal power curve. The MPPT algorithm makes it easier for the WECS to operate at this curve. Therefore, the MPPT algorithm helps to record and monitor the maximum output power for WECS.

A. SUGGESTED MPPT METHODS

Selecting the right step is essential to preventing oscillations around the MPP and achieving faster tracking since the CPO technique tracks the MPP by scanning the rectified voltage's past and present values. There appears to be a trade-off between the two. The suggested method tackles this problem. The relationship between Vdc and Pdc [37] is shown in Figure 4, which also provides the choice of step size for CPO. One attains a maximum Pdc (MPP) for an ideal value of Vdc. The suggested method is developed using this relationship. The three stages that the suggested approach operates in are depicted in Figure 6. The Vdc-Pdc plot is split into equal-width trapezoids in the first phase using the trapezoidal rule. To determine the values of maximum area and power, the second step compares the current and prior trapezoids. Figure 7 illustrates this theme. These data are used to implement the FLC and track the MPP in the third phase. In Figure 8, the fundamental FLC framework is displayed. The values obtained following the application of the trapezoidal rule are Pout and Vout. The FLC receives these values as well. The input error, represented by "e," and the change in error, represented by "ec," are derived using the ratio of δP and δV, which are found in Equations 5 and 6. The FLC inputs "e" and "ec" are specified by Equations 7, 8, and 9, respectively. Centroid is the defuzzification technique and Mamdani is the FIS type utilized. The implication and aggregation procedures are defined as minimum (min) and maximum (max),

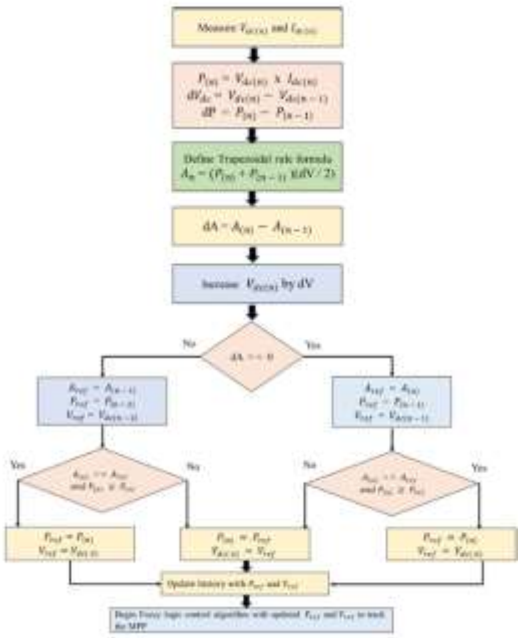

FIGURE 5. Procedure of the proposed MPPT method.

in turn. FLC has the ability to properly track variations in wind speed. The inputs "e" and "ec," which are sent to the controller, are fuzzed to create the fuzzy set. In order to provide the proper fuzzy output, the inference system uses the fuzzy rules to process the fuzzy set. Following defuzzification, the fuzzy output is ultimately transformed to the duty cycle, which is then utilized to further regulate the boost converter's switching element and enable MPP tracking.

$$\delta P = P_{(n)} - P_{(n-1)} \quad (5)$$

$$\delta V = V_{(n)} - V_{(n-1)} \quad (6)$$

$$e_{(n)} = \delta P/\delta V \quad (7)$$

$$ec = e_{(n)} - e_{(n-1)} \quad (8)$$

The membership function for the inputs "e," "ec," and "D" is displayed in Figures 9, 10, and 11. These membership functions have seven variables defined: Nbig, Nmed, Nsmall, Zero, Psmall, Pmed, and Pbig. The fuzzy rules' intricate reasoning is as follows:

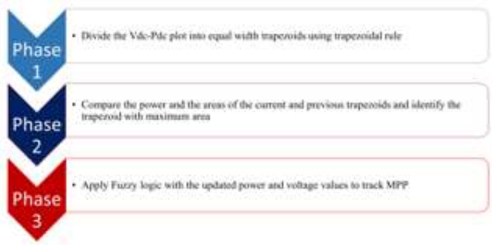

FIGURE 6. Phases of the proposed technique.

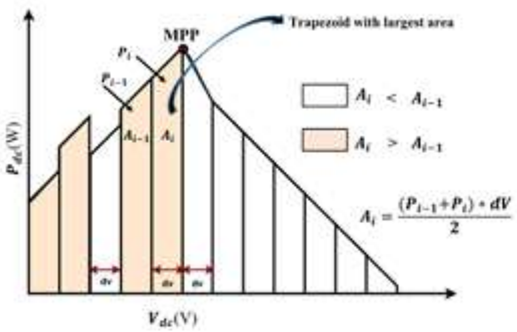

FIGURE 7. Theme of the proposed technique

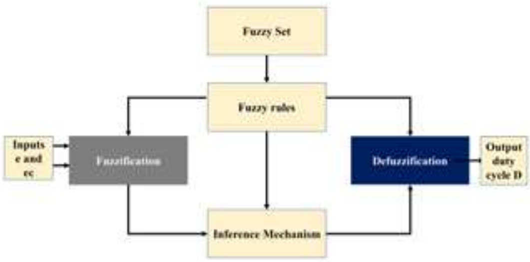

FIGURE 8. Basic frame work of FLC.

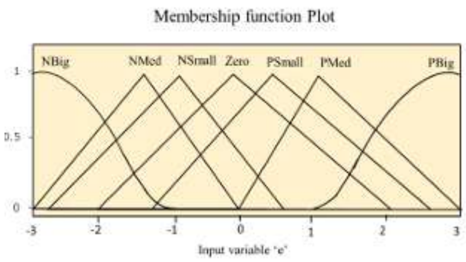

FIGURE 9. FLC input e membership function.

D = Zero if e = NBig and ec = NBig.

D=Zero if e = NBig and ec = NMed;

D = 0 if e = NBig and ec = NSmall.

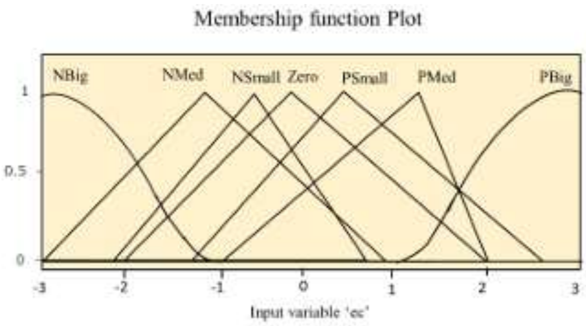

FIGURE 10. FLC input ec membership function.

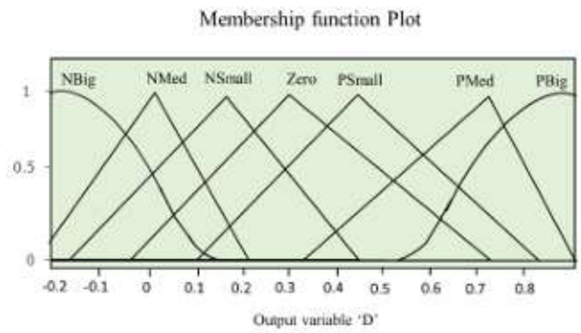

FIGURE 11. FLC output D membership function.

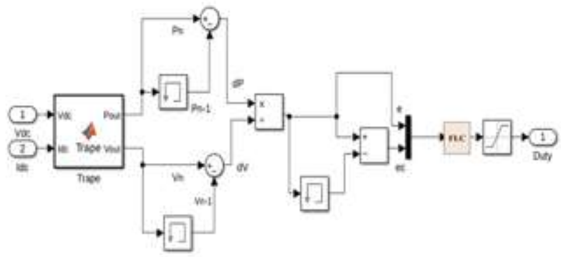

FIGURE 12. Fuzzy logic applied after trapezoidal rule in the proposed algorithm.

Table 2 displays the 49 rules that are framed for FLC. Figure 12 displays the FLC block diagram that was used during simulation. Figure 5 shows the comprehensive process.

III. CPO SIMULATION AND THE SUGGESTED METHODS

The WECS model with the TRPO, CPO, and suggested trapezoidal rule-based FLC MPPT methods blocks is displayed in Figure 13 and is simulated using MATLAB/Simulink.

The WECS simulates one technique at a time using a manual switch. The simulated system's parameters are shown in Table 3. The Simulink CPO block is displayed in Figure 14. The TRPO method's Simulink model is displayed in Figure 15, and the technique's blocks are shown in Figure 16.

TABLE 2. Rules for FLC.

Output D		Input 'e'						
Input 'ec'		NBig	NMed	NSmall	Zero	PSmall	PMed	PBig
	NBig	Zero	Zero	NSmall	NMed	PSmall	PMed	PBig
	NMed	Zero	Zero	Zero	NSmall	PMed	PMed	PBig
	NSmall	Zero	Zero	Zero	Zero	PMed	PMed	PBig
	Zero	NBig	NSmall	Zero	Zero	PSmall	Zero	Zero
	PSmall	NBig	NMed	NSmall	Zero	Zero	Zero	Zero
	PMed	NBig	NMed	NSmall	PSmall	Zero	Zero	Zero
	PBig	NMed	NMed	NSmall	PMed	Zero	Zero	Zero

TABLE 3. Simulation system parameters.

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WT Parameters	Value and unit
Radius	3.01m
Air density	$1.22 kg/m^3$
Rated Power	1 Kilo Watt
β	0
PMSG Parameters	**Value and unit**
Rated Power	1 Kilo Watt
Pole pairs	2
Rs	1.6 Ω
Ld=Lq	6.3 miliHenry
J	$8.54\ kgm^2$
Boost converter Parameters	**Value and unit**
L	75 miliHenry
C	0.468 μFarads
Switching frequency	5KHz
RL	54 Ω

suggested. The power coefficient for each of the three methods is shown in Figure 17. The random fluctuation in wind speed utilized to simulate all three methods is shown in Figure 18. The suggested technique's curve is shown in red, TRPO's in light blue, and the CPO method's in navy blue. The relative voltage, current, and DC output power attained with each of the three methods are displayed in Figures 19, 20, and 21 correspondingly. These figures' A, B, C, D, and E markings show the improved output power, voltage, and current as well as the decrease in oscillations. These figures make it clear that the suggested method helps to lessen oscillations and increase the power produced at the output.

IV. OUTCOMES

The TRPO, CPO, and the suggested MATLAB/Simulink approach are all simulated in the preceding section. The power coefficient for each of the three methods is shown in Figure 17. Table 3 provides specifics about the simulated system's specs. Figure 18 illustrates the differences in wind speed. Higher produced voltage, current, and power are shown by the graphs presented in Figures 19, 20, and 21, respectively. The contrast between the

TABLE 4. Comparison of the rise time. response time and the transient time of all the three simulated techniques.

Name of the MPPT algorithm	Rise time (m sec)	Transient time (m sec)	Response time (m sec)
Trapezoidal rule based Fuzzy logic	0.1231	6.9450	0.035
Trapezoidal rule based PO	0.2133	6.9450	0.040
Conventional P&O	0.3200	6.9700	0.060

TABLE 5. Comparison of the tracking efficiency for all the three techniques at the rated wind speed of 5 m/s.

Name of the MPPT algorithm	MPPTracking efficiency
Trapezoidal rule based Fuzzy logic	99.1%
Trapezoidal rule based P&O	92.7%
Conventional P&O	87%

The superiority of the suggested algorithm is demonstrated by the technique used with the other two. These figures' sections A, B, C, and D show increased power yielded at the output and fewer oscillations. For each of the three approaches, the wind speed was varied at random from 4, 5, 4, 3, and 5 m/sec. The rated wind speed of 5 m/s yields the maximum simulated power output for all approaches. The suggested TRPO and CPO approaches have duty cycle maximums of 0.37, 0.302, and 0.29, respectively. Table 4 displays the comparison of the rise time, response time, and transient time of the three simulated approaches. There is a 0.6%, 6.8%, and 1.06% increase in voltage, current, and power at the output with the adoption of the TRPO method compared to CPO, respectively. From the comparison shown in Table 4, it is clear that the presented technique provides a faster response in tracking the MPP. Table 5 demonstrates that the tracking efficiency of the proposed technique while tracking the MPP is maximum among all three techniques; Table 6 shows the superiority of the proposed technique.

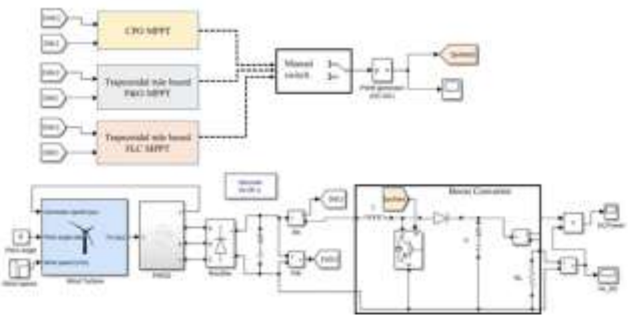

FIGURE 13. Simulation Model in MATLAB/Simulink for the TRPO, CPO and the proposed algorithm.

TABLE 6. Comparison of the MPPT techniques.

Parameters of the MPPT technique	TSR [15], [45]–[48]	PSF [15], [45], [46]	OT [15], [45]–[48]	CPO [15], [45]–[48]	INC [15], [45]–[48]	ORB [15], [45]–[48]	NN [45], [47]	TRPO [45]	Proposed Technique
Efficiency of Tracking MPP	High	Moderate	Moderate	Low	Low	Moderate	High	High	High
Convergence speed	High	High	High	Low	Low	Medium	High	High	High
Oscillations near the MPP	No	No	No	Yes	Yes	No	No	No	No
Training data requirement	No	Yes	Yes	No	No	No	Yes	No	No
Wind speed estimation sensor requirement	Yes	Yes	No	No	No	No	Depends	No	No
Performance under changing wind speed	High	Moderate	High	Moderate	Moderate	Moderate	High	High	Excellent

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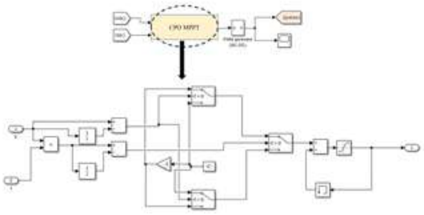

FIGURE 14. CPO technique SIMULINK block.

improved using the suggested FLC technique based on the Trapezoidal rule, which shows an increase of 8.02% in DC output power, 6.14% in DC output voltage, and 6.14% in DC output current over CPO. The Trapezoidal based FLC methodology, which is the suggested method, produces 5.4%, 5.4%, and 7.36% more

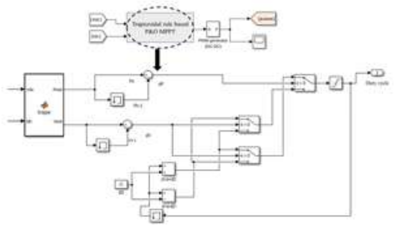

FIGURE 15. SIMULINK block for TRPO algorithm.

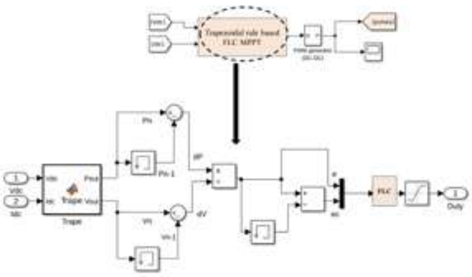

FIGURE 16. Simulation block for the presented technique in MATLAB/Simulink.

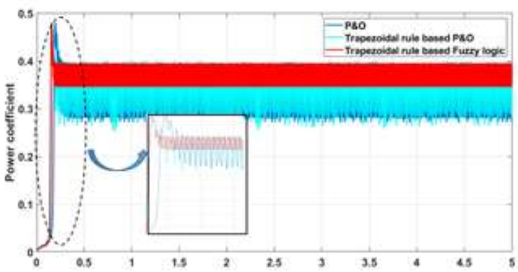

FIGURE 17. Plot of the Power coefficient

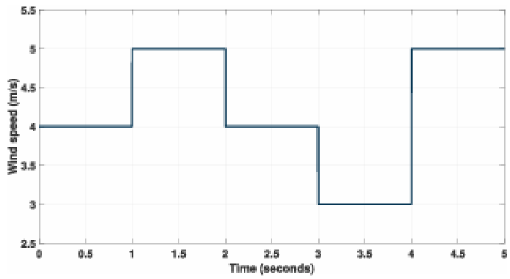

FIGURE 18. Profile of variation in the wind speed.

V. DISCUSSION

There are many different MPPT methods for WECS available in the literature, and one of the performance parameters in the existing methods presented for tracking the MPP can be improved at the expense of another. The most difficult task is to improve the system performance for highly fluctuating wind conditions while yielding maximum power with the aid of the MPPT technique with minimal computational burden and oscillations around MPP. MPPT-based optimization techniques are quite evident, but they seem to suffer from issues such as a higher computational burden for MPP tracking. The most recent hybrid methods available can resolve the problems of conventional techniques, but are found to be complex during the implementation process, necessitates simple methods for this purpose.

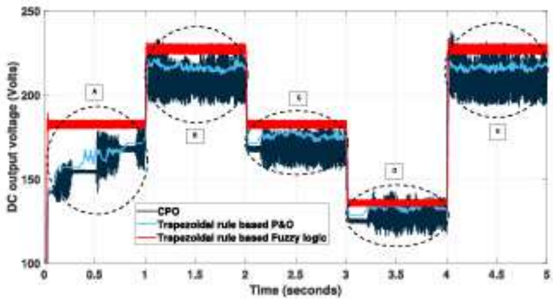

FIGURE 19. Plot of Time and output Voltage.

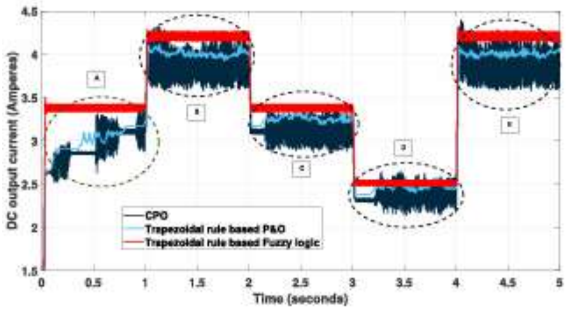

FIGURE 20. Plot of Time and output Current.

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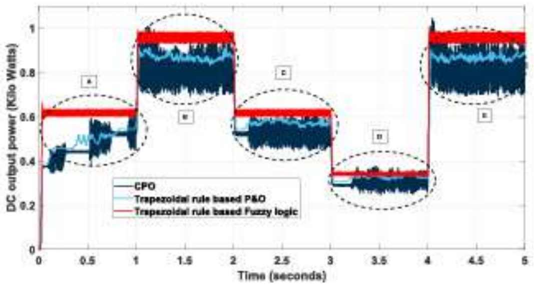


FIGURE 21. Plot of Time and output Power.

ANN Architecture

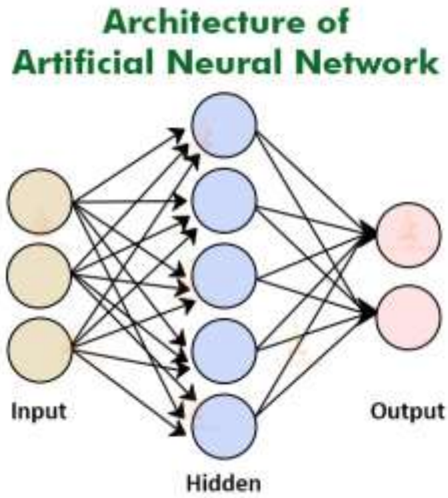
- "For MPPT in the hybrid system, we used a feedforward neural network (FFNN) – a good choice for handling wind/solar non-linearities.
- The FFNN has an input layer (wind speed 'Vw' (m/s), solar irradiance 'G' (W/m²), PV voltage 'Vpv' (V), PV current 'Ipv' (A)), two hidden layers (10 neurons each, ReLU activation), and an output layer (duty cycles 'd_wind', 'd_solar' (0-1 range)).
- ReLU is efficient and avoids vanishing gradients."

ANN Training Process

- "We trained the ANN on 10,000 samples from MATLAB/Simulink (Vw: 0-25 m/s, 0.1 m/s steps; G: 0-1000 W/m², 10 W/m² steps).
- The Adam optimizer (learning rate: 0.001, beta1: 0.9, beta2: 0.999, epsilon: 1e-7) was used with 32-sample mini-batches.
- We used Mean Squared Error (MSE) as the loss function and 10-fold cross-validation to prevent overfitting.
- Inputs were normalized to 0-1 using min-max scaling for better training."

ANN Inputs and Outputs

- "The ANN inputs are: Vw (m/s), G (W/m²), Vpv (V), Ipv (A).
- The outputs are duty cycles (0-1): d_wind (wind converter), d_solar (solar converter).
- These control DC-DC converters for maximum power extraction."



Why Use an ANN?

- "ANNs are effective for MPPT because they handle the non-linearities of wind/solar systems.
- They adapt well to changing conditions, improving power capture.
- Compared to Fuzzy Logic Control, ANNs learn from data, potentially capturing more complex behavior.
- Unlike metaheuristic algorithms, ANNs offer a good balance of accuracy and real-time computation."

WORKING OF WIND SOLAR WITH ANN:

The approach used in the presented work is based on the trapezoidal rule merged with the FLC method. The MPP tracking process does not require speed sensors, and the proposed technique reduces oscillations with enhanced power. Future research can be based on combining numerical methods and several existing approaches to further enhance system performance and obtain quicker tracking and improved power extraction from WECS.

Figure 21 presents a block diagram representation of a **wind power system**. According to the **Betz limit**, a maximum of **59%** of the wind's kinetic energy can be converted into mechanical energy by a wind turbine (WT). This limitation arises because some wind energy must remain to allow airflow past the turbine. The **mechanical power (Pm)** extracted by the wind turbine is determined using **Equation (1)**:

Pm=0.5·Cp·ρ·A·V3P_m = 0.5 \cdot C_p \cdot \rho \cdot A \cdot V^3Pm=0.5·Cp·ρ·A·V3

where:

- PmP_mPm = Mechanical power extracted (W)

- CpC_pCp = Power coefficient (efficiency factor of the turbine)
- ρ\rhoρ = Air density (kg/m³)
- AAA = Swept area of turbine blades (m²)
- VVV = Wind velocity (m/s)

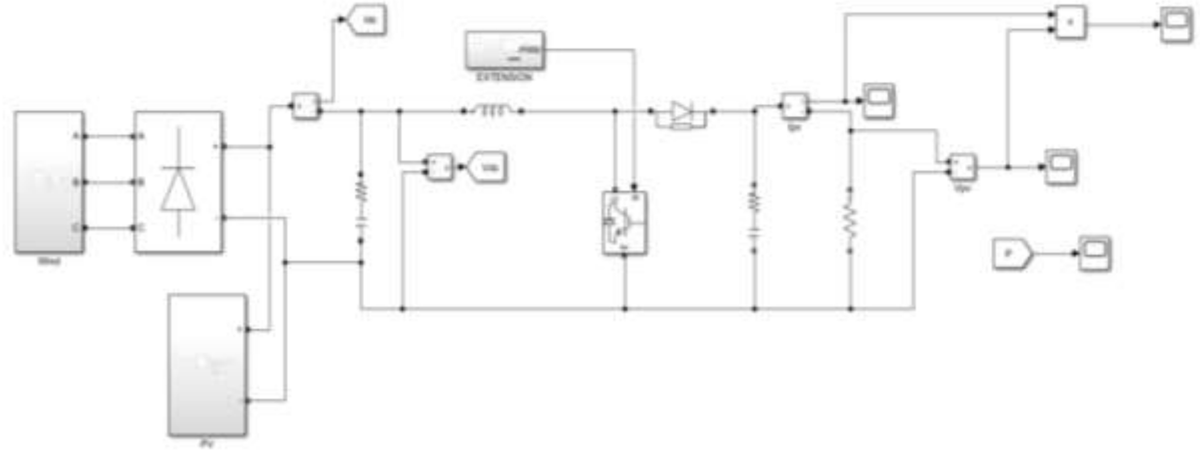


Figure 21: Block diagram of solar and wind with ANN

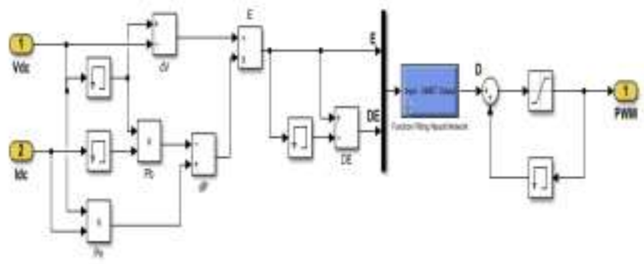


Figure 22 : Simulation block for the ANN MPPT technique in MATLAB/Simulink.

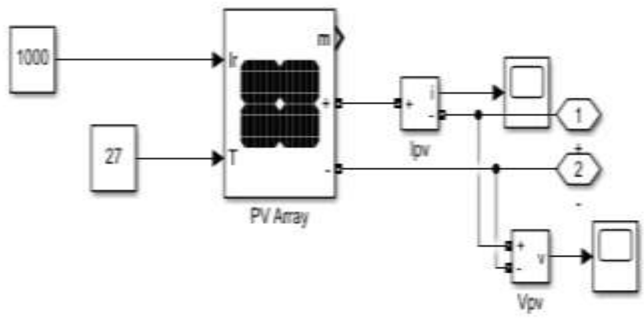


Figure 23 : Simulation block for the PV in MATLAB/Simulink.

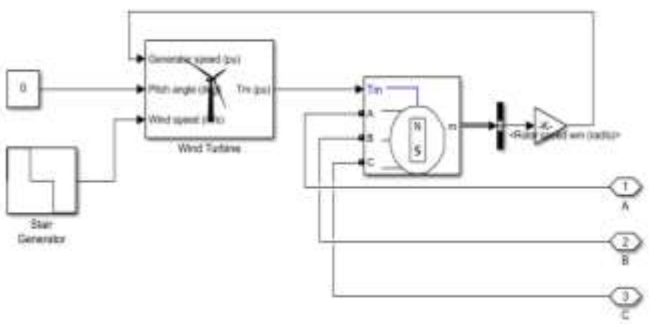


Figure 24 : Simulation block for the Wind in MATLAB/Simulink.

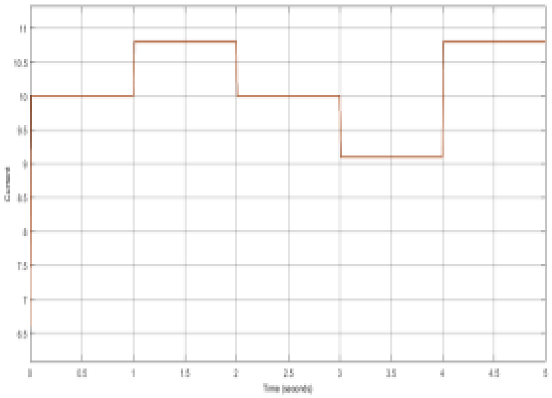


Figure 22: Plot of Time and output Current.

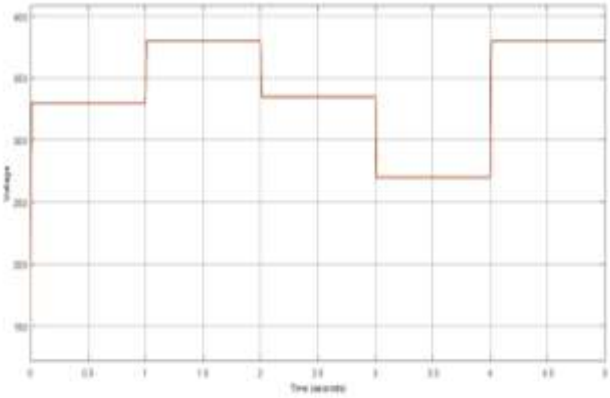


Figure 23: Plot of Time and output Voltage

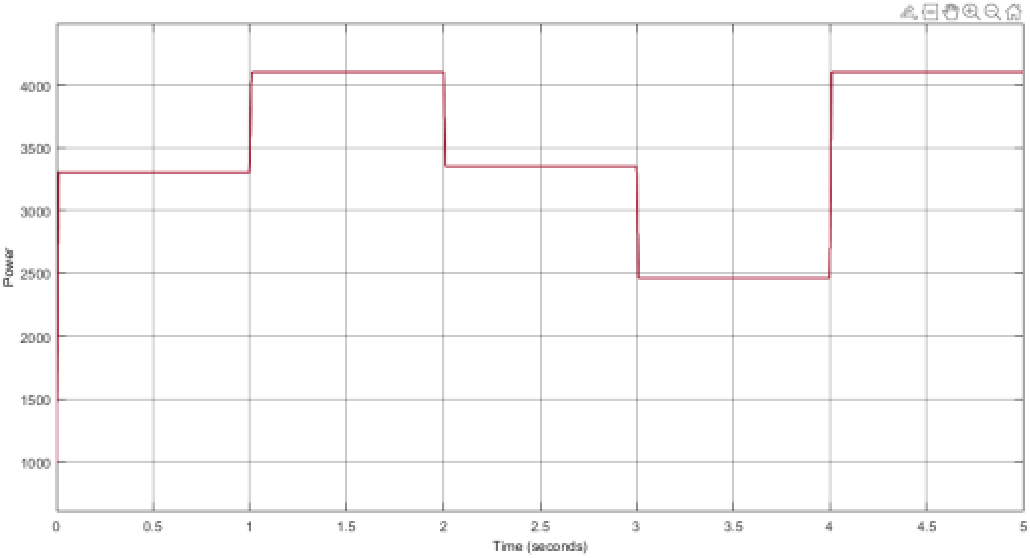


Figure 24 : Plot of Time and output Power.

The **power contained in the air (Pair)** before interaction with the turbine is given by **Equation (2)**:

Pair=0.5·ρ·A·V3P_{air} = 0.5 \cdot \rho \cdot A \cdot V^3Pair=0.5·ρ·A·V3

where the parameters remain the same.

The **radius (R)** of the rotor blades determines the swept area of the turbine, given by **Equation (3)**:

A=πR2A = \pi R^2A=πR2

where:

- RRR = Blade radius (m)

The **power coefficient (Cp)** depends on the **Tip Speed Ratio (TSR, denoted as λ\lambdaλ)** and the **blade pitch angle**. The TSR is defined as:

λ=ωRV\lambda = \frac{\omega R}{V}λ=VωR

where:

- ω\omegaω = Angular velocity of the turbine (rad/sec)

Integration of Wind-Solar Hybrid System with ANN

To enhance power generation efficiency, a hybrid **wind-solar energy system** is considered, where both renewable sources contribute to the total energy output. The inclusion of an **Artificial Neural Network (ANN)** further improves **Maximum Power Point Tracking (MPPT)** by adapting to changing environmental conditions and optimizing power extraction. In the following sections, we will explore the implementation of the proposed method using numerical techniques and intelligent control algorithms to maximize power efficiency.

The **power contained in the wind (Pair)** and the power absorbed by the **Wind Turbine (WT)** are related to the Betz limit, which dictates that no more than **59%** of the wind's energy can be harvested by the turbine. This limitation is a fundamental characteristic of wind energy conversion. The relevant equations for mechanical power extraction and wind power, along with the turbine's swept area and radius, are detailed in **Equations (1), (2), (3), and (4)**, which can be found in [26].

Mechanical Energy Conversion

The generator stage receives input from the wind turbine, facilitating the conversion of **mechanical energy** into **electrical energy**. A **three-phase rectifier** converts the generator's three-phase output into direct current (DC). The **Maximum Power Point Tracking (MPPT)** algorithm regulates the **DC-DC boost converter**, which boosts the DC voltage. This process is controlled through a **Pulse Width Modulation (PWM)** generator, which receives the duty cycle produced by the MPPT algorithm. By adjusting the duty cycle, the PWM controls the switching element in the boost converter, increasing the output voltage and, consequently, the overall power.

Wind Turbine Output Power Zones

The wind turbine operates in different output power zones. These zones are defined as follows:

- **Zone 1:** This region represents wind speeds that are too low for the wind turbine to generate any power.
- **Zone 2:** Between the **cut-in** and **rated wind speeds**, the turbine starts generating power, and this range is critical for maximizing efficiency through MPPT.
- **Zone 3:** In this region, as wind speeds exceed the rated wind speed, the turbine's power output begins to plateau.

Integration of Wind and Solar Energy with ANN

To optimize energy generation further, a **hybrid wind-solar energy system** is employed. This system combines the benefits of both renewable sources to meet energy demands more effectively. An **Artificial Neural Network (ANN)** is used to improve the performance of the **MPPT algorithm**, allowing the system to adapt dynamically to varying wind and solar conditions. The ANN helps predict the maximum power point more efficiently, adjusting the duty cycle for both wind and solar power inputs.

- **Wind Energy System (WECS):** The wind energy conversion system captures energy from the wind through a wind turbine and generator.
- **Solar Energy System (PV):** The solar power system uses photovoltaic (PV) panels to generate electricity from sunlight.
- **ANN Extension:** The ANN model is integrated to optimize MPPT for both wind and solar inputs, enhancing the system's efficiency and reducing energy losses caused by environmental fluctuations.

By combining these systems and using advanced control algorithms, the hybrid system maximizes energy capture and stability, providing a reliable and efficient renewable energy solution.

Selecting the appropriate **step size** is crucial to avoiding **oscillations around the Maximum Power Point (MPP)** and ensuring **fast tracking**. The **Conventional Perturb and Observe (CPO) algorithm** achieves MPP tracking by analyzing **past and present rectified voltage values**, which introduces a trade-off between stability and tracking speed. The proposed method effectively addresses this issue.

Relationship Between VdcV_{dc}Vdc and PdcP_{dc}Pdc

The relationship between **DC voltage (VdcV_{dc}Vdc)** and **DC power (PdcP_{dc}Pdc)**, plays a vital role in selecting the step size for CPO. The **Maximum Power Point (MPP)** is reached when PdcP_{dc}Pdc is maximized for an optimal VdcV_{dc}Vdc value. The **proposed method is designed using this relationship**, ensuring efficient tracking with minimal power loss.

Three-Stage Operation of the Proposed Method

The **proposed MPPT algorithm** operates in three key stages

1. **Trapezoidal Rule-Based Voltage Partitioning**

The **Vdc-Pdc** plot is divided into **equal-width trapezoidal sections** using the **trapezoidal numerical integration method**.

This approach ensures accurate power estimation across different voltage levels.

Comparison of Current and Previous Trapezoidal Areas

The areas under the trapezoidal segments are compared between consecutive iterations.

The maximum **power region** and **reference voltage** are determined dynamically.

Fuzzy Logic Control (FLC) for MPP Tracking

The trapezoidal rule provides **output power (PoutP_{out}Pout)** and **output voltage (VoutV_{out}Vout)**, which serve as inputs for FLC.

The input **error (e)** and the **change in error (ec)** are computed based on **perturbation values δP\delta PδP and δV\delta VδV**, as described in **Equations (5) and (6)**.

The fuzzy logic input equations are specified in **Equations (7), (8), and (9)**.

Fuzzy Inference System (FIS) Design

The FLC system employs:

- **Mamdani-type Fuzzy Inference System (FIS)**
- **Defuzzification using the Centroid method**
- **Minimum (min) for implication and Maximum (max) for aggregation**

Hybrid Wind-Solar System with ANN-Based MPPT

To further **optimize power tracking**, the **proposed MPPT method** is integrated with a **hybrid wind-solar energy system**, incorporating an **Artificial Neural Network (ANN)** for enhanced decision-making:

- **Wind Energy Conversion System (WECS)**: Converts wind energy to electricity using wind turbines, generators, and power converters.
- **Solar Photovoltaic (PV) System**: Converts sunlight into electricity, complementing wind power generation.
- **ANN Extension**: The ANN is trained on varying environmental conditions and provides dynamic adjustments to MPPT, enhancing efficiency under fluctuating wind and solar inputs.

This **intelligent hybrid approach** eliminates the limitations of traditional methods, ensuring **rapid, stable, and highly efficient MPPT tracking** across varying environmental conditions.

		Base Paper Output Result			Project Output Result
S.No	**Parameters**	**CPO**	**TRPO**	**TRFL**	**ANN**
1	Voltage In DC (Vdc)	130 V	150 V	180 V	340 V
2	Current In DC (Idc)	2.6 Amps	2.8 Amps	3.5 Amps	10 Amps
3	Power In DC (Pdc)	0.38 kw	0.4 kw	0.65 kw	3.4 kw

TABLE 7. Comparison of the MPPT techniques.

CPO	Conventional Perturb And Observe
TRPO	Trapezoidal Rule Based PO
TRFL	Trapezoidal Rule Based Fuzzy logic
ANN	Aritifical Neural Network

CONCLUSION

The current state of MPPT (Maximum Power Point Tracking) algorithms for Wind Energy Conversion Systems (WECS) illustrates a wide range of tracking strategies, from traditional methods to advanced soft computing techniques and optimization-focused approaches. While these modern methods have proven effective in accurately tracking the MPP, they often suffer from increased implementation complexity, making them less practical for real-time or low-cost applications. As a result, there is a strong demand for simpler, more efficient tracking techniques. Earlier research has explored combinations of traditional strategies such as the Constant Power Output (CPO) method with numerical approaches like the trapezoidal rule. Building on this, the method proposed in this work introduces a hybrid approach that integrates a trapezoidal rule-based technique with Fuzzy Logic Control (FLC), further enhanced by an Artificial Neural Network (ANN). This three-stage method begins by dividing the Vdc-Pdc curve into equal-width trapezoids using the trapezoidal rule. In the second stage, the trapezoid corresponding to the highest power output is identified. The final stage uses FLC to track the MPP within that trapezoid using the power and voltage values identified, while the ANN adaptively learns from the system's behavior to improve tracking accuracy and response under dynamic wind conditions. This approach eliminates the need for a wind speed sensor and enhances the robustness and efficiency of the tracking process. Comparative analysis with CPO and the Trapezoidal Rule-based Power Optimization (TRPO) methods under randomly varying wind speeds (4, 5, 4, 3, and 5 m/s) shows that while all methods achieve peak power at a rated wind speed of 5 m/s, the proposed technique outperforms the others significantly. Specifically, the TRPO method provides 0.6%, 6.8%, and 1% better output in terms of voltage, current, and power respectively compared to CPO. The proposed trapezoidal rule-based FLC with ANN yields 5.4%, 5.4%, and 7.36% more output in DC voltage, current, and power respectively compared to the TRPO method. Compared to CPO, it achieves an 8.02% increase in power, and a 6.14% increase in both voltage and current. The simulation results and graphical analyses confirm the substantial improvement in power extraction using the proposed method. Future research could further explore integrating hybrid, intelligent, conventional, and numerical techniques to develop simplified yet high-performance MPPT strategies, enabling faster tracking and greater energy harvesting from WECS.

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