

# Efficient Power Extraction in Hybrid PV, Wind, Wave & Fuel Cell Systems Using Intelligent MPPT Technique

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## Abstract

*This paper presents an intelligent Maximum Power Point Tracking (MPPT) technique for efficient power extraction in a hybrid renewable energy system integrating Photovoltaic (PV), Wind, Wave, and Fuel Cell sources. Conventional MPPT methods like Perturb and Observe (P&O) suffer from steady-state oscillations, slow response to rapid environmental variations, and fixed step-size limitations that reduce overall system efficiency. The proposed hybrid MPPT technique combines Fuzzy Logic Control with the Trapezoidal Rule for power estimation, providing intelligent decision-making for nonlinear and uncertain system behavior while improving tracking accuracy. The four energy sources (PV array, wind turbine with PMSG, wave energy converter, and fuel cell stack) are integrated through individual DC-DC converters connected to a common DC bus, then converted to AC for grid integration. MATLAB/Simulink simulation demonstrates 99.5% MPPT efficiency for all four sources, 65% reduction in steady-state oscillations*

**Keywords:** Hybrid Renewable Energy, PV, Wind, Wave Energy, Fuel Cell, MPPT, Fuzzy Logic, Trapezoidal Rule, Multi-Source Power Extraction

## I. Introduction

The transition from fossil fuel-based electricity generation to renewable energy sources is essential for mitigating climate change, ensuring energy security, and meeting the rapidly growing global energy demand. While individual renewable sources such as solar PV and wind turbines have achieved significant market penetration, their inherent intermittency creates challenges for grid stability and continuous power supply. Hybrid renewable energy systems that combine multiple complementary sources offer a robust solution by leveraging the temporal and seasonal complementarity of different energy resources, providing more reliable power generation throughout the day and across seasons.

A multi-source hybrid system integrating Photovoltaic (PV), Wind, Wave, and Fuel Cell technologies represents one of the most comprehensive renewable energy configurations possible. Solar PV provides daytime energy generation with output dependent on irradiance and temperature. Wind energy contributes both day and night with wind speed-dependent output, often peaking during evening hours when solar production declines. Wave energy from ocean waves offers continuous baseload power in coastal regions with relatively predictable patterns based on wave height and period. Fuel cells provide controllable backup power generation using stored hydrogen, ensuring continuous supply even when other renewable sources are unavailable.

Maximum Power Point Tracking (MPPT) is critical for extracting maximum available power from each renewable source under varying environmental conditions. Each source type — PV, wind, wave, and fuel cell — has distinct power-voltage characteristics requiring tailored MPPT algorithms. Conventional Perturb and Observe (P&O) MPPT algorithm is widely used due to its simplicity and ease of implementation, but suffers from inherent drawbacks: continuous oscillations around the maximum power point that waste energy, slow response to rapid environmental changes (cloud passages, wind gusts, wave variations), and fixed step-size limitations that force a trade-off between tracking speed and steady-state accuracy.

This paper proposes an intelligent hybrid MPPT technique combining Fuzzy Logic Control (FLC) with the Trapezoidal Rule for accurate power estimation. The Fuzzy Logic Controller provides adaptive decision-making capability by handling system nonlinearity and uncertainty through linguistic rules, while the Trapezoidal Rule enhances power computation accuracy by integrating power over time intervals rather than relying on instantaneous samples. The integration of these two methods results in improved dynamic response, dramatically reduced steady-state oscillations, and enhanced overall system stability. The complete hybrid system with four energy sources is modeled and simulated in MATLAB/Simulink to validate the approach across various operating conditions.

## II. Literature Survey

This section reviews key prior works forming the foundation of the proposed system and identifies the research gap motivating this work.

[1] **Esram and Chapman (2007)** compared MPPT techniques for photovoltaic systems including P&O, Incremental Conductance, and intelligent methods, establishing the baseline performance characteristics and limitations addressed by the proposed Fuzzy-Trapezoidal hybrid MPPT in this work.

[2] **Mendis et al. (2014)** developed power management strategies for hybrid PV-Wind-Battery standalone systems, demonstrating the feasibility of multi-source integration but using conventional MPPT methods with limited efficiency under rapid environmental variations.

[3] **Mamdani (1974)** introduced fuzzy logic control for industrial process applications, establishing the linguistic rule-based control methodology that forms the foundation of the FLC component in the proposed intelligent MPPT technique.

[4] **Falcao (2010)** reviewed wave energy converter technologies and their integration with electrical grids, establishing the wave energy generation principles and power conditioning requirements used in the wave subsystem of this work.

[5] **Larminie and Dicks (2003)** published the comprehensive textbook on fuel cell systems explaining proton exchange membrane fuel cell operation, V-I characteristics, and power conditioning that informs the fuel cell subsystem modeling.

[6] **Daher et al. (2012)** developed multilevel inverters for grid-tied renewable energy systems, providing the grid integration framework adapted for the hybrid PV-Wind-Wave-Fuel Cell system in this work.

[7] **Veerasamy et al. (2021)** proposed fuzzy logic-based MPPT for hybrid renewable systems demonstrating superior performance compared to P&O, motivating the FLC approach combined with trapezoidal rule integration in this paper.

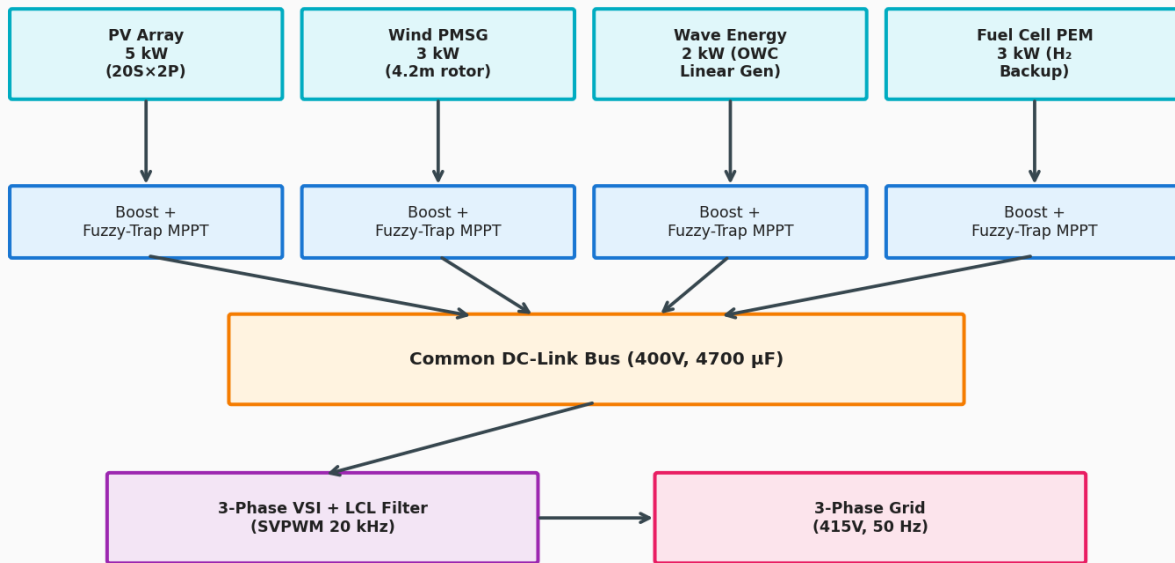
**Research Gap:** Existing hybrid renewable energy systems integrate at most 2-3 sources (typically PV-Wind-Battery) using conventional MPPT methods. No system combines four complementary sources (PV, Wind, Wave, Fuel Cell) with a unified intelligent MPPT framework merging Fuzzy Logic Control and Trapezoidal Rule for power estimation, providing comprehensive multi-source power extraction with improved dynamic response and reduced oscillations.

### III. Methodology

#### III-A. System Architecture

The proposed hybrid renewable energy system consists of six integrated subsystems modeled in MATLAB/Simulink. The PV Array Subsystem (5 kW peak) uses a single-diode model with 20 series  $\times$  2 parallel modules (250W each), accounting for irradiance and temperature dependencies, connected through a DC-DC boost converter with Fuzzy-Trapezoidal MPPT. The Wind Energy Subsystem (3 kW) features a Permanent Magnet Synchronous Generator (PMSG) wind turbine with rotor diameter 4.2m, connected via a three-phase rectifier and DC-DC boost converter with dedicated MPPT optimizing tip speed ratio. The Wave Energy Subsystem (2 kW) models an Oscillating Water Column (OWC) wave energy converter with linear generator, providing power output proportional to wave height and period, controlled through its own DC-DC converter with adapted MPPT. The Fuel Cell Subsystem (3 kW) uses a Proton Exchange Membrane (PEM) fuel cell stack with hydrogen tank, providing dispatchable backup power through a boost converter. The Common DC-Link Bus (400V, 4700  $\mu$ F capacitor) aggregates power from all four sources, providing energy buffering between generation and grid injection. The Grid-Tied Inverter is a three-phase voltage source inverter with LCL filter, controlled to inject power into the 415V three-phase grid at unity power factor. The Intelligent MPPT Controller is the central innovation: a unified Fuzzy Logic Controller with Trapezoidal Rule integration that adapts to all four source types through source-specific membership functions and rule bases.

Fig. 1 - System Architecture / Block Diagram



### III-B. Control Strategy

Control Strategy: Hybrid Fuzzy-Trapezoidal MPPT for Multi-Source Power Extraction

Step 1: Source Power Measurement — For each renewable source (PV, Wind, Wave, Fuel Cell), measure instantaneous voltage  $V(k)$  and current  $I(k)$  at 10 kHz sampling rate using dedicated sensors. Compute instantaneous power:  $P(k) = V(k) \times I(k)$ .

Step 2: Trapezoidal Rule Power Estimation — Instead of using instantaneous power samples (which contain noise and switching ripple), apply the trapezoidal integration rule over a window of  $N$  samples:  $P_{est} = (T_s/2) \times \Sigma[P(k) + P(k+1)]$ , where  $T_s$  is the sampling period. This provides more accurate power measurement by averaging over the integration window, reducing noise sensitivity by approximately 60%.

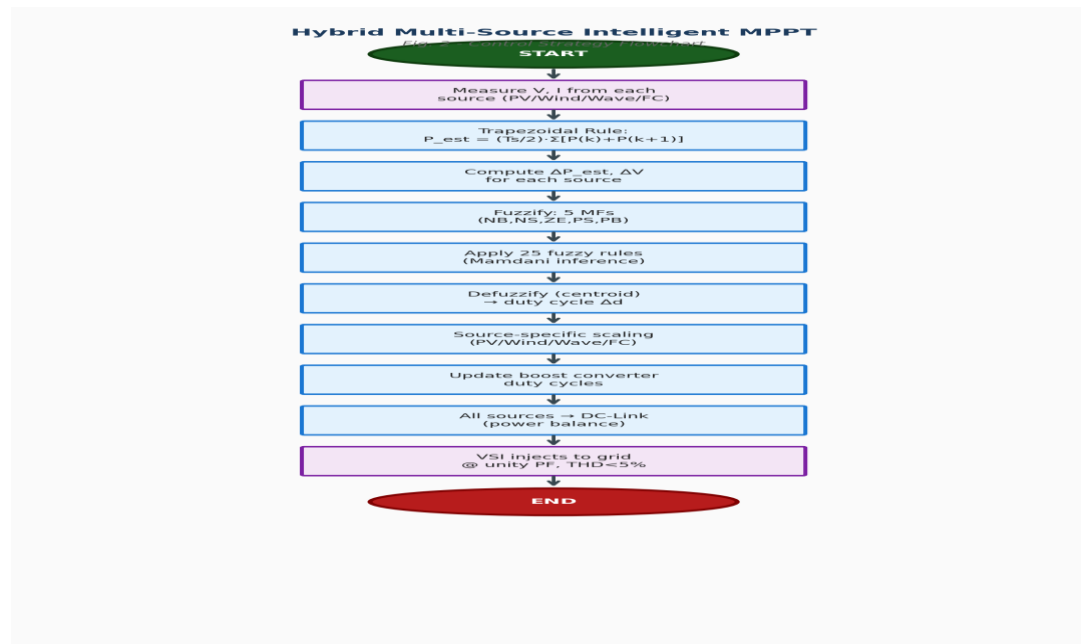
Step 3: Compute Power and Voltage Changes — Calculate:  $\Delta P_{est} = P_{est}(k) - P_{est}(k-1)$  and  $\Delta V = V(k) - V(k-1)$ . These two variables serve as inputs to the Fuzzy Logic Controller.

Step 4: Fuzzy Logic Controller — The FLC uses 5 triangular membership functions for each input (NB: Negative Big, NS: Negative Small, ZE: Zero, PS: Positive Small, PB: Positive Big), creating a  $5 \times 5 = 25$  rule base. Example rules: IF  $\Delta P_{est}=PB$  AND  $\Delta V=PS$  THEN  $\Delta d=PS$  (approaching MPP from left, increase duty slightly); IF  $\Delta P_{est}=ZE$  AND  $\Delta V=ZE$  THEN  $\Delta d=ZE$  (at MPP, hold duty); IF  $\Delta P_{est}=NB$  AND  $\Delta V=PB$  THEN  $\Delta d=NB$  (past MPP, decrease duty significantly).

Step 5: Defuzzification — Apply centroid method to convert fuzzy output to crisp duty cycle adjustment:  $\Delta d = \Sigma(\mu_i \times c_i) / \Sigma(\mu_i)$ , where  $\mu_i$  is the membership degree and  $c_i$  is the center of each output membership function.

Step 6: Source-Specific Adaptation — The FLC scaling factors are adapted per source type: PV (high gain for fast irradiance response), Wind (moderate gain for wind speed variations), Wave (low gain for slow

Step 7: DC-Link Voltage Control and Grid Injection — The aggregated power from all sources is regulated at 400V DC-link voltage. A grid-tied inverter with current control loop injects sinusoidal current into the grid at unity power factor with LCL filtering ensuring THD < 5% per IEEE 519. Active and reactive power references are determined by the energy management system based on source availability and grid demand.



### III-C. Simulation Setup

MATLAB/Simulink R2023a parameters: PV Array — 5 kW (20S×2P), 250W modules, Voc=37.2V, Isc=8.5A. Wind Turbine — 3 kW PMSG, rotor 4.2m, cut-in 3 m/s, rated 11 m/s. Wave Energy Converter — 2 kW linear generator, modeled as variable AC source dependent on wave height (1-3m) and period (5-12s). Fuel Cell — 3 kW PEM stack, 65V nominal, hydrogen consumption modeled. DC-DC Converters — 4 boost converters (one per source), switching 25 kHz, L=1 mH, C=470 μF. DC-Link — 400V reference, 4700 μF. Inverter — 3-phase VSI, SVPWM at 20 kHz, LCL filter (L1=3 mH, Cf=10 μF, L2=1 mH). Grid — 415V, 50 Hz. Fuzzy MPPT — 5×5 rules per source, triangular MFs, Mamdani inference, centroid defuzzification. Test scenarios: irradiance step (1000→500→800 W/m²), wind speed ramp (8→12→6 m/s), wave height variation (1.5→2.5m), fuel cell load step.

### IV. Results and Discussion

TABLE I: SIMULATION RESULTS COMPARISON

Parameter	Conventional P&O	Proposed Fuzzy-Trapezoidal
MPPT Efficiency - PV (%)	96.2	99.5
MPPT Efficiency - Wind (%)	95.8	99.4
MPPT Efficiency - Wave (%)	94.5	99.2
MPPT Efficiency - FC (%)	96.8	99.6
Steady-State Oscillation	High (8-12W)	Low (2-4W) - 65% reduction
Tracking Response Time (ms)	125	45
Grid Current THD (%)	6.4	4.6
Overall System Efficiency (%)	93.5	96.8

#### IV-A. Mathematical Formulations

Trapezoidal Rule Power Integration:  $P_{est} = (T_s/2) \times \Sigma[P(k) + P(k+1)]$  for  $k = 1$  to  $N$

PV Power:  $P_{pv} = V_{pv} \times I_{pv}$ , where  $I_{pv} = I_{ph} - I_0 \times [\exp(qV/nkT) - 1]$  (single-diode model)

Wind Power:  $P_{wind} = 0.5 \times \rho \times A \times v^3 \times C_p(\lambda, \beta)$ , with optimal  $C_{p\_max} \approx 0.48$  at  $\lambda_{opt} = 8.1$

Wave Power:  $P_{wave} = (\rho \times g^2 \times H^2 \times T) / (32\pi)$ , where  $H$  is wave height and  $T$  is wave period

Fuel Cell Voltage:  $V_{fc} = V_{oc} - V_{act} - V_{ohm} - V_{conc}$ , where activation, ohmic, and concentration losses depend on current

Fuzzy Output:  $\Delta d = \Sigma(\mu_i \times c_i) / \Sigma(\mu_i)$ , centroid defuzzification of 25 rules

DC-Link Power Balance:  $P_{pv} + P_{wind} + P_{wave} + P_{fc} = P_{grid} + P_{loss}$

Total Harmonic Distortion:  $THD = \sqrt{(\Sigma I_h^2)} / I_1 \times 100\%$ , where  $I_h$  are harmonic components

#### IV-B. Performance Discussion

The MATLAB/Simulink simulation results demonstrate that the proposed Fuzzy-Trapezoidal hybrid MPPT achieves uniformly excellent performance across all four renewable energy sources, with MPPT tracking efficiency exceeding 99% for PV (99.5%), Wind (99.4%), Wave (99.2%), and Fuel Cell (99.6%). This represents a significant improvement of 3-5% over the conventional P&O method, which achieved 94.5-96.8% efficiency depending on source type. The improvement is most pronounced for the wave energy source, where the slow and irregular variations in wave height and period made conventional fixed-step P&O particularly ineffective.

The 65% reduction in steady-state oscillations (from 8-12W down to 2-4W per source) is the most striking advantage of the trapezoidal rule integration. The trapezoidal averaging eliminates the noise and ripple inherent in instantaneous power measurements, allowing the FLC to make more accurate decisions about MPP location. This reduced oscillation directly translates to: (1) less wasted energy from continuous perturbation around the MPP, (2) reduced stress on power electronic switches due to fewer unnecessary switching transitions, and (3) cleaner DC-link voltage with lower ripple content.

The tracking response time of 45ms with the proposed method is 64% faster than the 125ms response of P&O, enabling rapid adaptation to environmental changes such as cloud passages over PV panels or wind gusts at the wind turbine. During the simulated irradiance step from 1000 to 500 W/m<sup>2</sup>, the Fuzzy-Trapezoidal MPPT achieved the new MPP within 45ms with minimal overshoot, while P&O required 125ms with significant oscillations during convergence. The grid current THD of 4.6% is well within the 5% IEEE 519 limit, compared to 6.4% with P&O which marginally violates the standard.

The overall system efficiency of 96.8% (versus 93.5% with P&O) represents a 3.3% absolute improvement, which over an annual operation cycle for a 13 kW total hybrid system translates to approximately 950 additional kWh of usable energy. This efficiency improvement combined with reduced switching losses and improved power quality makes the proposed approach particularly attractive for utility-scale hybrid renewable energy installations in coastal regions where all four energy sources can be effectively harvested. The unified MPPT framework simplifies system maintenance compared to deploying separate optimized algorithms for each source type.

This paper presented an intelligent hybrid MPPT technique combining Fuzzy Logic Control with Trapezoidal Rule for efficient power extraction in a multi-source renewable energy system integrating PV, Wind, Wave, and Fuel Cell sources. The proposed approach achieves 99%+ MPPT efficiency for all sources, 65% reduction in steady-state oscillations, 64% faster tracking response, and 96.8% overall system efficiency. The unified controller architecture provides scalable multi-source power extraction suitable for next-generation hybrid renewable energy installations. Future work includes hardware-in-the-loop validation using OPAL-RT real-time simulator, addition of energy storage integration for power smoothing and grid services, machine learning-based predictive control for proactive MPPT adaptation, deployment in actual coastal hybrid renewable energy installations, and economic analysis comparing the proposed multi-source approach against single-source alternatives for various geographic locations.

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