

# Hybrid ANN-INC MPPT Integrated with a High-Efficiency Boost VMS Converter for Photovoltaic Systems

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## ABSTRACT

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### Keywords

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The primary aim of this research is to present a hybrid maximum power point tracking (MPPT) algorithm that overcomes oscillation, slow response and high losses faced by conventional MPPT algorithms. The proposed hybrid technique combines artificial neural network (ANN) and incremental conductance (INC) MPPT. It intelligently switches between ANN and INC algorithms according irradiance level. At high irradiance which typically occurs under clear sky conditions, ANN is applied to achieve rapid and predictive tracking. For reduced irradiance levels below 400 W/m<sup>2</sup> that represents cloudy weather, INC is activated for stable performance. Besides, the hybrid ANN-INC MPPT is paired with an advanced boost voltage multiplier stage (VMS) converter to obtain a lower duty cycle and a higher voltage gain and consequently reducing switching and conduction losses during conversion. The entire system is simulated in MATLAB/ Simulink to investigate its performance under varying irradiance and load conditions. The results demonstrate the proposed system superior performance across all evaluated scenarios. Under high irradiance (1000 W/m<sup>2</sup>), the system reached a highest power of 398.283 W within a response time of 1.056 seconds and achieved a peak overall efficiency of 93.911%. Furthermore, under moderate irradiance (400 W/m<sup>2</sup>), it maintained the highest output power of 152.35 W and a peak overall efficiency of 95%. Under dynamic irradiance conditions, the system sustained a steady power of 155.524 W at the low irradiance plateau demonstrating stability and recovery. The synergistic operation of the presented hybrid ANN-INC MPPT with the low-loss boost VMS converter is confirmed as a significant breakthrough. Its high power and efficiency as well as smooth voltage and current signals make it effective for practical applications where finding true peak fast and accurately is a major challenge.

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## 1. Introduction

Solar energy production relies on the Photovoltaic (PV) panel is an essential technology that directly converts sunlight into electricity using the photoelectric effect [1], [2]. Its importance stems from its role as a clean the renewable energy source that directly addresses global climate change concerns and energy security through a decrease in dependency on fossil fuels [3], [4]. However, the electrical characteristics of a PV panel are highly nonlinear and dependent on external factors like solar irradiance and temperature. This dependence means that the voltage and current at which the maximum power point (MPP) is achieved are continuously changing. To ensure maximum energy capture, it is critically important to integrate an MPPT algorithm with a DC/DC converter [5]–[7]. The MPPT tracks the highest possible power from the panel, while the DC/DC converter acts as the intermediary boosting the PV generated voltage and adjusting the electrical load seen by the panel. Traditional MPPT methods are widely utilized but suffer from fundamental disadvantages that limit overall system efficiency and speed. Perturb and Observe (P&O) is known for its simplicity; however, after the maximum is reached its primary flaw is the tendency to fluctuate around the MPP leading to unnecessary power losses. Incremental conductance (INC) improves upon P&O by using the variation in power/voltage ratio to eliminate oscillation and improve tracking speed under rapid fluctuations of irradiance.

Similarly, particle swarm optimization (PSO) and other stochastic methods offer better global tracking under complex partial shading conditions but often suffer from slow convergence speeds [8]–[11]. At the same time, the boost converter which increases voltage is one of the most often used conventional DC/DC converter types in PV systems [12]–[15]. However, a boost converter requires an extremely high duty cycle to achieve a large voltage step-up, which in turn leads to significant and conduction losses, directly reducing the overall conversion efficiency. As a result, pairing MPPT algorithms with conventional boost converters deteriorates the system efficiency. Thus, it is imperative to form optimal combinations of MPPT algorithms and DC/DC converters that achieve fast tracking and low power loss which is the main motivation of this work.

The Proposed System is a cutting-edge dual optimization solution that integrates a hybrid ANN-INC MPPT with an advanced boost voltage multiplier stage (VMS) converter [16]–[20]. The hybrid MPPT intelligently switches to the ANN for rapid and predictive tracking during high irradiance and defaults to the stable INC for lower irradiance levels ensuring optimal power extraction speed and stability. That effectively solves the traditional MPPT tradeoff between speed and oscillation. At the same time, the boost VMS converter addresses the efficacy gap of the conventional boost converter by using voltage multiplier cell to reach a high voltage gain with a more moderate lower duty cycle, which drastically reduces power loss during the conversion stage and boosts the overall power transfer efficiency. The synergistic combination delivers the highest power, superior overall efficiency and a cleaner output signal that none of the conventional systems can match.

The structure of the remainder of the paper: [Section 2](#) details the methodology and mathematical models, that including the proposed system, converter topologies and MPPT algorithms (ANN, INC, ANN-INC). [Section 3](#) presents the numerical results and analysis for each simulation scenario. Finally, [Section 4](#) provides the conclusions and outlines potential future work.

## 2. Method

### 2.1. Maximum Power Point Tracking

#### 2.1.1. Artificial Neural Network (ANN) MPPT

The Artificial Neural Network (ANN) MPPT is implemented as an intelligent nonlinear control technique that forms the core of the hybrid tracking strategy within the high-performance regime of the photovoltaic (PV) system. Unlike the conventional algorithms that rely on iterative comparisons, that based on real time input parameters like voltage, current and irradiance the ANN-based MPPT uses a model that has been trained to quickly and correctly estimate the PV array ideal operating point.

That predictive capability is critical for maximizing power harvest, which particularly when the solar irradiance is high specifically within the demanding range of  $1000 \text{ W/m}^2$  down to  $400 \text{ W/m}^2$ . In that phase ANN is activated to exploit its key advantage: the ability to quickly eventually reach the global maximum power point (MPP) without the need for repetitive system perturbations. By rapidly tracking the MPP the ANN minimizes transient tracking time and the associated energy loss, that ensuring minimal power wastage during periods of high solar insolation. The predictive nature enables the ANN to effectively bypass the inherent oscillations and slow convergence characteristic of hill climbing methods under high irradiance and rapidly changing conditions thereby contributing pointedly to the overall stability and efficiency of the proposed system at peak performance levels [21]. Fig. 1 shows the flowchart of ANN MPPT.

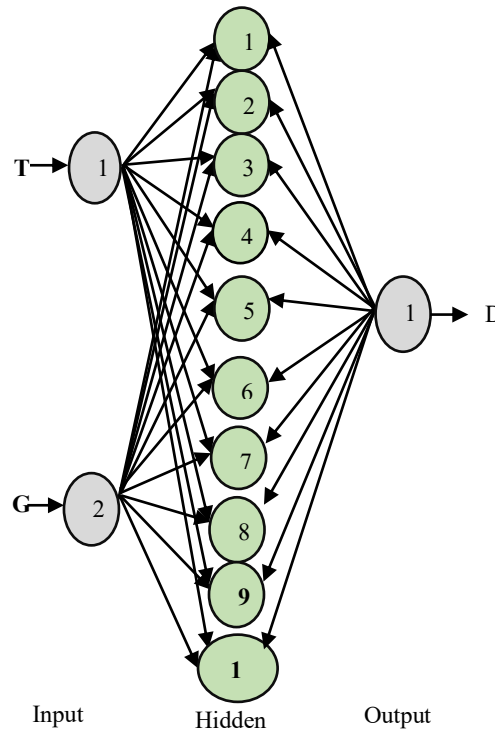


Fig. 1. ANN architecture for maximum power point tracking control [22]

### 2.1.2. Incremental Conductance (INC) MPPT

The Incremental Conductance (INC) MPPT algorithm serves as the secondary robust component of the hybrid strategy, that providing a reliable fallback for operation under lower and more stable irradiance conditions. The INC method is a conventional hill climbing technique that operates by continuously comparing the incremental conductance  $\frac{dI}{dV}$  of the PV array with the instantaneous conductance  $\frac{I}{V}$ . By monitoring the sign of the changes in power with respect to voltage  $\frac{dP}{dV}$  the algorithm determines whether to increase or decrease the duty cycle of the converter to ensure the operating point moves closer to the MPP. That straightforward perturbation and observation process makes the INC method easy to implement and inherently stable. In the proposed methodology the system transitions to the INC algorithm when the solar irradiance drops to, below, fluctuates around the  $400 \text{ W/m}^2$ . The operational assignment is strategic, capitalizing on the INC reliability in stable lower-irradiance environments where the tracking speed requirements are less critical. While the INC is stable its fundamental limitation is that it must continuously perturb the system to find the maximum, which that leads to power oscillations around the MPP and slower convergence times compared to the ANN, that making it less suitable for the high irradiance dynamic conditions where the ANN is employed [23]. Fig. 2 shows the INC MPPT flowchart for the PV panel system.

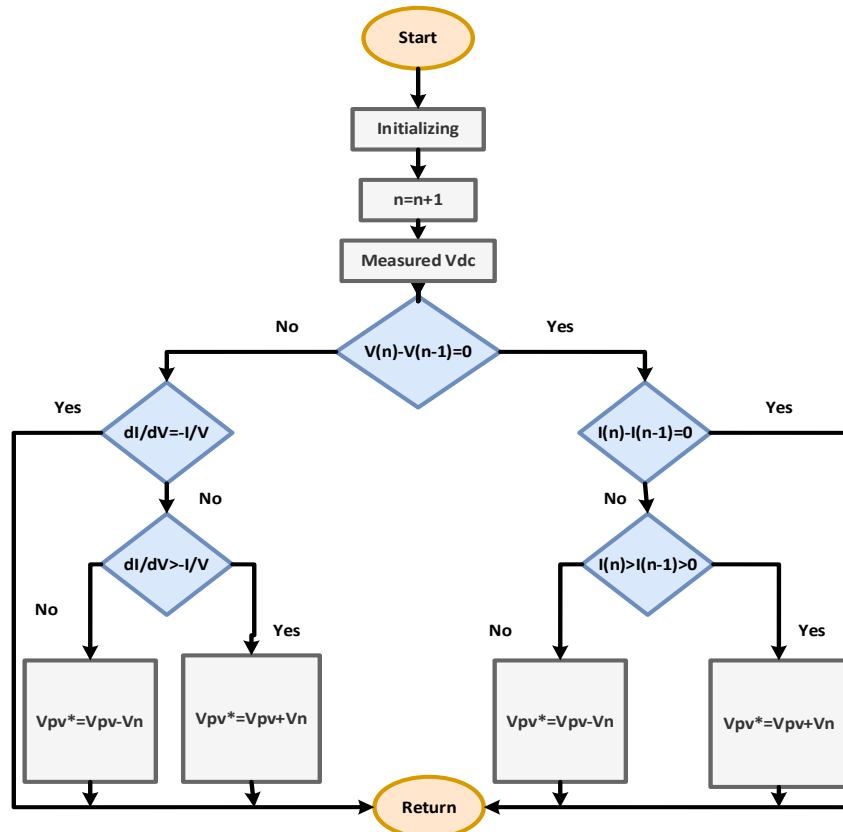


Fig. 2. INC maximum power point tracking flowchart algorithm [24]

### 2.1.3. Hybrid ANN-INC

The proposed methodology for the Maximum Power Point Tracking (MPPT) system employs a hybrid approach that integrates an Artificial Neural Network (ANN) with a conventional Incremental Conductance (INC) algorithm. The intelligent switching mechanism is designed to optimize the performance of the photovoltaic (PV) system across a wide range of irradiance conditions. The ANN based MPPT which is pre-trained to accurately and rapidly predict the optimal operating point is activated when the solar irradiance is high specifically within the range of  $1000 \text{ W/m}^2$  to  $400 \text{ W/m}^2$ . The phase leverages the ANN ability to quickly converge to the global maximum power point (MPP) that minimizing tracking time and energy loss during periods of high solar insolation. Conversely the system transitions to the INC algorithm when the irradiance drops to  $400 \text{ W/m}^2$ . The INC method which relies on a simple and robust "hill-climbing" technique to perturb the system and track the MPP is well-suited for stable lower-irradiance conditions. By combining these two techniques the proposed system aims to capitalize on the strengths of each algorithm: the swift and efficient tracking of the ANN at high power levels and the reliable, also stable performance of the INC at lower irradiance, that resulting in a robust and highly efficient overall MPPT solution [25], [26]. Fig. 3 shows the proposed hybrid ANN-INC MPPT.

## 2.2. DC/DC Converter

### 2.2.1. Boost Converter

The conventional boost converter is established as the baseline DC/DC topology against which the performance of the advanced boost VMS converter is measured that serving as the power processing stage for three of the four evaluated system groups. The function of the basic converter is to step up the low input voltage ( $V_{PV}$ ) supplied by the PV panel to a higher output voltage ( $V_o$ ) required by the load or subsequent inverter stages. The standard configuration typically consists of a single inductor, a main power switch, a diode and an output capacitor. The output voltage is directly

regulated by the duty cycle (D) of the switch the governed by the theoretical voltage gain relationship:  $M = \frac{V_o}{V_{PV}} = \frac{1}{1-D}$  However in PV applications where a large voltage step up is often necessary the conventional boost converter faces a fundamental efficiency limitation to achieve a high voltage gain it requires an extremely high duty cycle. Operating at such high duty cycles detrimentally increases both the switching and conduction losses within the power switch and diode, resulting in significantly lower conversion efficiency at high voltage gains. The inherent power loss during the conversion stage ultimately restricts the overall power transfer efficiency of the entire PV system a critical flaw that the advanced Voltage Multiplier Stage (VMS) topology is designed to overcome. Table 1 details of the boost converter used in the study [27].

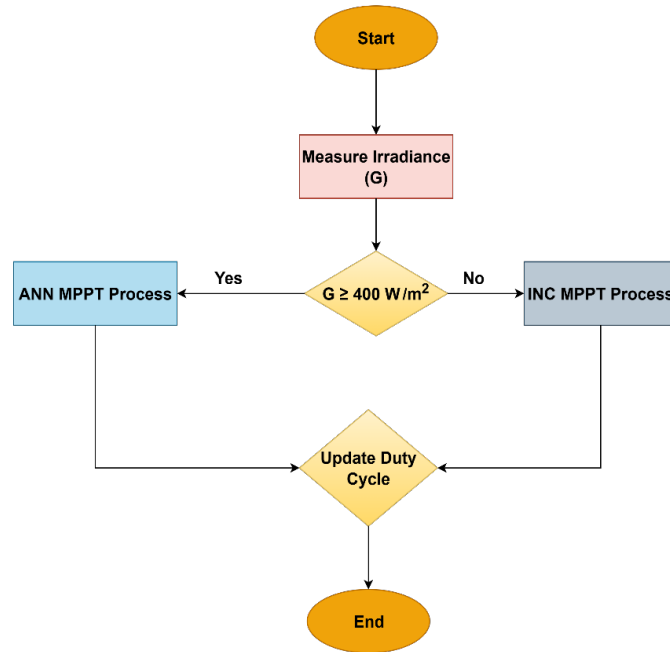


Fig. 3. Flowchart for A hybrid ANN-INC Maximum Power Point Tracking (MPPT) algorithm

Table 1. The boost converter parameters

Parameter	Value
Input capacitance $C_{boost}$	$781.25 \cdot 10^{-6}$ F
Inductance	$12.14 \cdot 10^{-6}$ H

When the switch is closed, the diode is reverse-biased. Around the path, including the closed switch, inductor, and source indicated in (1) the Kirchhoff's voltage law is applied [28].

$$v_L = V_{PV} = L \frac{di_t}{dt} \tag{1}$$

Here is ( $\delta$ ) the duty cycle, ( $v_L$ ) is the inductors voltage across it., ( $V_{PV}$ ) is the BIPV panels terminal voltage., and (L) is the boost converter inductor.

The diode becomes forward-biased when the switch is opened that creating a channel for the inductor current. It prevents the inductor current from changing instantly. When the output voltage  $V_o$  is in (2) the voltage across the inductor remains constant.

$$v_L = V_{PV} - V_o = L \frac{di_L}{dt} \tag{2}$$

From (3), the calculation of the output voltage ( $V_o$ ),

$$V_o = \frac{V_{PV}}{1 - \delta} \quad (3)$$

The average values of (4) and (5) and the variation in current are used to calculate the maximum and minimum inductor currents.

$$I_{max} = I_L + \frac{\Delta i_L}{2} = \frac{V_{PV}}{(1 - \delta)^2 R_{load}} + \frac{V_{PV} \delta T}{2L} \quad (4)$$

$$I_{min} = I_L - \frac{\Delta i_L}{2} = \frac{V_{PV}}{(1 - \delta)^2 R_{load}} - \frac{V_{PV} \delta T}{2L} \quad (5)$$

Where ( $I_L$ ) is the current through inductor.

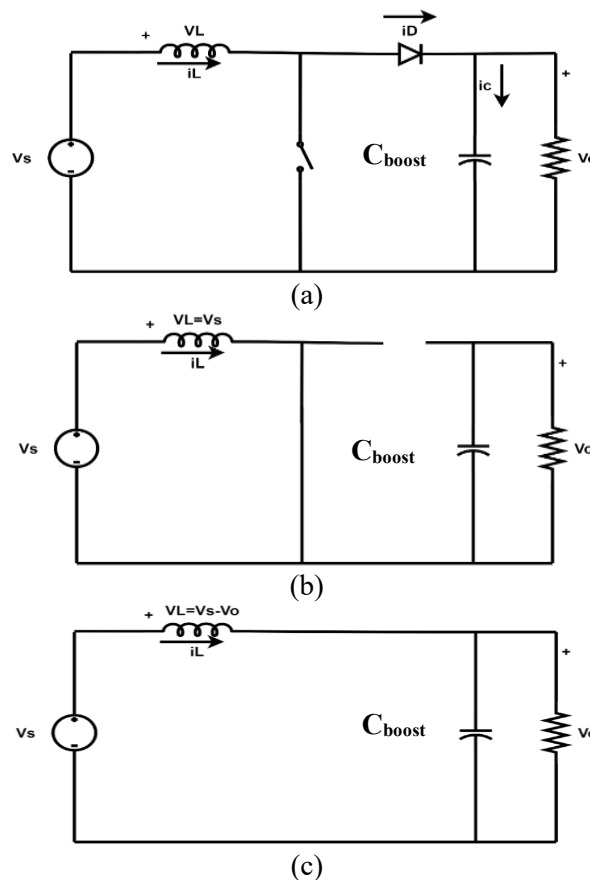
It is helpful to express L in terms of a desired  $\Delta i_L$ , from a design standpoint.

$$L = \frac{V_{PV} \delta T}{\Delta i_L} = \frac{V_{PV} \delta}{\Delta i_L f} \quad (6)$$

With the switching frequency denoted by f. As an alternative, capacitance is described as the ripple in the output voltage yields.

$$C_{boost} = \frac{\delta}{R_{load} \left( \frac{\Delta V_o}{V_o} \right) f_{sw}} \quad (7)$$

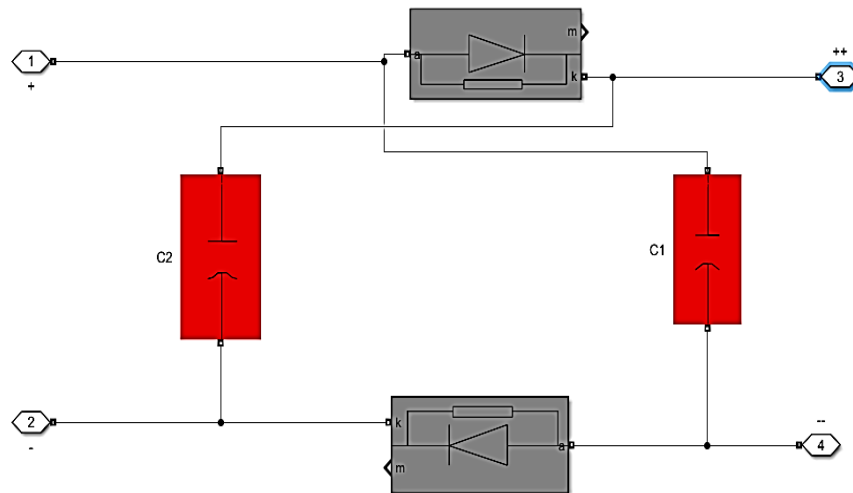
The boost converter equivalent circuit is given in Fig. 4.



**Fig. 4.** The boost converter: (a) circuit; (b) circuit equivalent for the closed switch; (c) circuit equivalent for the open switch

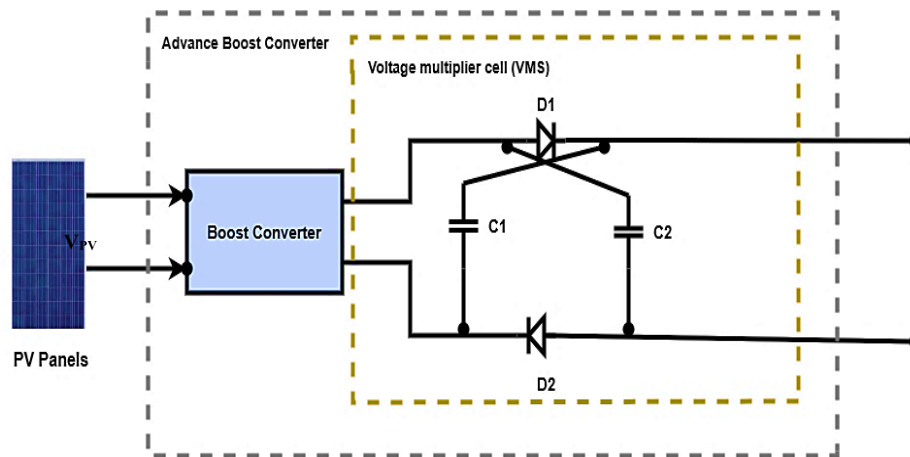
**2.2.2. Boost VMS Converter**

The methodology for the advanced boost voltage multiplier stage (VMS) converter focuses on achieving a high voltage gain with improved efficiency and reduced component stress. Unlike conventional boost converters which require an extremely high duty cycle to produce a large voltage step-up the VMS topology incorporates an additional circuit stage composed of diodes and capacitors. The voltage multiplier cell works to "multiply" the voltage gain that allowing for a much higher output voltage without the detrimental effects of a high duty cycle such as increased switching and conduction losses. That is crucial for PV applications since the solar panel's input voltage is frequently low and must be greatly increased to satisfy the demands of the load or an inverter that comes after [29], [30]. Fig. 5 shows the boost VMS converter circuit.



**Fig. 5.** Boost Voltage Multiplier Stage (VMS) converter circuit in MATLAB/Simulink

Depending on the primary power device's switching status, the VMS converter can operate in a variety of modes. When the switch is ON, the inductor stores energy, and the capacitors within the VMS cell are charged. During this period, the load is typically supplied by other capacitors in the circuit. The inductor's stored energy is released when the switch is turned off, and its voltage is added to the input voltage. That combined voltage charges the output capacitors and is further multiplied by the VMS cell which resulting in a much higher output voltage than a traditional boost converter could achieve at a comparable duty cycle. The design contributes to the system's overall high efficiency and dependability by improving the voltage conversion ratio and lowering the voltage stress on the main power switch and diodes, enabling the use of lower-rated, more efficient components. Fig. 6 shows the advanced boost VMS converter connected with PV panels [31].



**Fig. 6.** Schematic of an advanced boost converter with voltage multiplier

The primary difference of lies in adding the VMS after the main switching stage. The traditional boost converter instantly increases the input voltage based on the duty cycle and the inductor energy storage. It typically has a single inductor, a switch, diode and an output capacitor [32]. That indicates that a basic boost converter voltage gain (M) is:

$$M = \frac{V_o}{V_{PV}} = \frac{1}{1 - D} \quad (8)$$

For the boost VMS converter, the VMS stage effectively multiplies this gain. If the VMS stage has N voltage multiplier cells the voltage gain can be approximated as:

$$M_{VMS} = \frac{V_o}{V_{PV}} = \frac{1 + N}{1 - D} \quad (9)$$

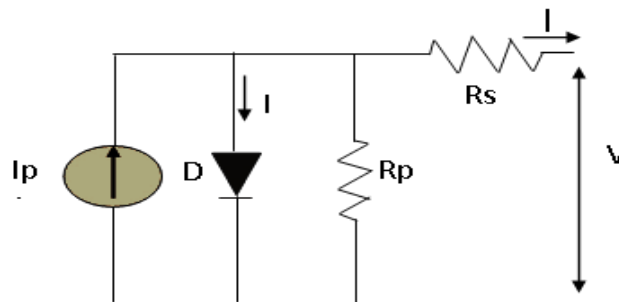
The formula illustrates the structural novelty: in comparison to a conventional boost converter the VMS stage offers that a larger voltage gain (1+N) for the same duty cycle (D). The lessens the voltage stress on the switching components and can be increase overall efficiency and reliability by enabling the converter to produce the same high output voltage with a shorter duty cycle. Table 2 shows the boost VMS converter parameters.

**Table 2.** Specifications of the Boost VMS converter

Parameter	Value
VMS capacitance $C_{1,2}$	$6.37 \times 10^{-6}$ F
VMS diodes (Snubber resistance, Snubber capacitance)	(500 $\Omega$ , $250 \times 10^{-9}$ F)

### 2.3. Photovoltaic (PV) Panel System

The primary energy source for the whole research system is the photovoltaic (PV) panel responsible for converting solar irradiance directly into electrical energy. Due to its inherent nonlinear power voltage characteristics the maximum power point (MPP) of the panel continuously shifts with environmental changes. Consequently, the panel output must be actively managed by the MPPT algorithm to ensure the highest possible power is consistently extracted. The generated low level DC voltage is fed directly into the advanced boost VMS converter which is tasked with conditioning the power and achieving the necessary high voltage gain for efficient delivery to the load. The suggested of the Hybrid ANN-INC MPPT and the boost VMS converter is vital for optimizing the PV panel performance and efficiency [33], [34]. Fig. 7 shows the circuit diagram of single-diode PV panel.



**Fig. 7.** PV module single-diode equivalent circuit

Mathematically the circuit can be expressed as follows [35],

$$I_{pv} = I_{ph} - I_d \left[ \exp \left( \frac{qV_{pv}}{k_b T A} \right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (10)$$

where  $A$  is the ideality factor,  $k_b$  is Boltzmann's constant,  $R_s$  is the series resistance,  $R_p$  is the parallel resistance,  $q$  is the charge of an electron,  $V_{pv}$  is the PV voltage,  $T$  is the PV module temperature,  $I_{ph}$  is the photocurrent produced by the PV cells, and  $I_d$  is the reverse saturation current of the single diode.

Fig. 8 shows the I-V and P-V characteristics of a PV panel under varying irradiance.

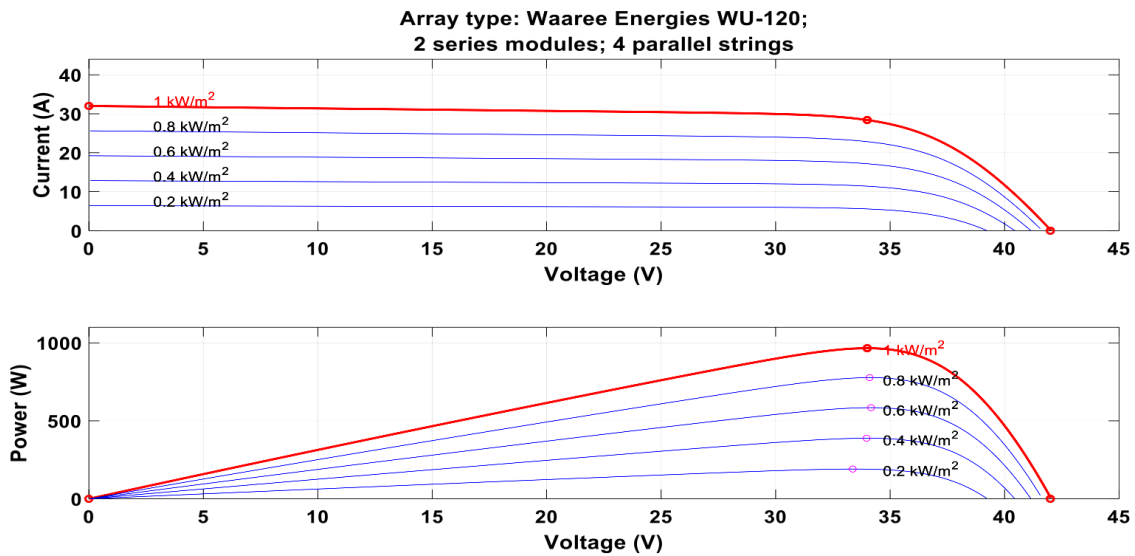


Fig. 8. I-V and P-V characteristics of a PV panel under varying irradiance

The PV panel specifications that were utilized are displayed in the Table 3. Fig. 9 shows the block diagram of the proposed system.

Table 3. Specifications of the Waaree Energies WU-120 PV Panel

Specification	Value	Unit
Module	Waaree Energies WU-120	-
Maximum Power (Pmax)	120.7	W
Open Circuit Voltage (Voc)	21	V
Short-Circuit Current (Isc)	8	A
Voltage at Maximum Power Point (Vmp)	17	V
Current at Maximum Power Point (Imp)	7.1	A
Cells per module (Ncell)	72	-
Temperature coefficient of Voc	-0.358	%/deg.C
Temperature coefficient of Isc	0.052	%/deg.C

### 3. Results and Discussion

The results of the research are structured around three distinct scenarios to comprehensively validate the performance of the Proposed System (Hybrid ANN-INC MPPT + boost VMS Converter) against the conventional configurations.

- **First Scenario: High Irradiance Test (1000 W/m<sup>2</sup>)**

This scenario was designed to test the peak performance and convergence speed of the MPPT algorithms and the overall power transfer. It specifically evaluates the efficiency of the ANN algorithm within the hybrid strategy, which is active at this high-power regime. The primary metrics measured are the time taken to reach the Maximum Power Point (MPP) (tracking speed) and the maximum overall power transfer efficiency.

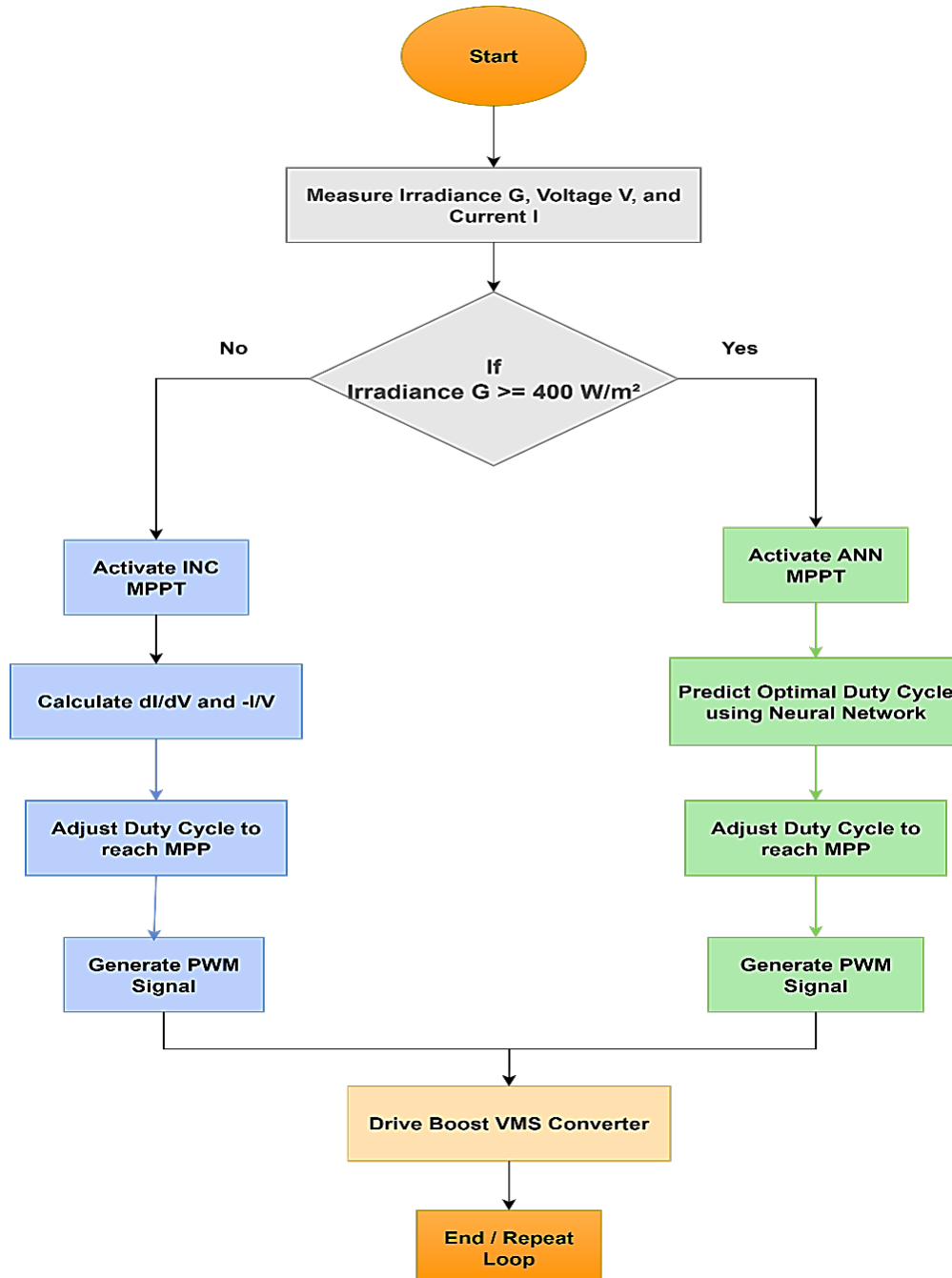
- **Second Scenario: Moderate Irradiance Test (400 W/m<sup>2</sup>)**

This scenario focuses on steady state performance at a critical operational threshold. It assesses the sustained power delivery and overall system efficiency when operating under lower but stable

solar input. That is crucial for confirming that the boost VMS converter maintains its low loss conversion advantage even when the power input from the PV panel is reduced.

- **Third Scenario: Global Irradiance ( $1000 \text{ W/m}^2$  to  $400 \text{ W/m}^2$ )**

This final and most complex scenario tests the system robustness and transient response under rapidly changing conditions. It specifically validates the effectiveness of the Hybrid ANN-INC intelligent switching mechanism, that evaluating how quickly the system recovers from a sharp drop in irradiance and how stable the output power remains during and after the transition.



**Fig. 9.** Block diagram of the proposed PV system integrated with a hybrid ANN-INC MPPT controller and Boost VMS converter

### 3.1. First Scenario Results

Fig. 10 demonstrates each system Maximum Power Point Tracking (MPPT) response at a high beam level of  $1000 \text{ W/m}^2$ . The proposed system demonstrates superior performance. The proposed system (Hybrid ANN-INC MPPT + boost VMS converter) reaches its maximum power point most rapidly that achieving a peak power of  $398.283 \text{ W}$  at approximately  $1.056$  seconds. In contrast, the conventional ANN-based system reaches a peak power of  $394.282 \text{ W}$  at a significantly slower time of  $2.87$  seconds while the standalone Incremental Conductance (INC) system only reaches  $378.191 \text{ W}$  at the same  $2.87$ -second mark. The hybrid ANN-INC with a conventional boost converter takes the longest to stabilize which reaching  $394.282 \text{ W}$  at nearly  $7$  seconds. The proposed system exceptional performance is primarily due to its intelligent hybrid MPPT strategy. At high irradiance levels the system leverages the Artificial Neural Network (ANN) algorithm, which is trained to quickly predict and track the MPP based on input parameters. The predictive capability allows it to converge on the optimal operating point much faster than iterative "hill-climbing" algorithms like INC which must perturb the system and observe the power change to find the maximum. The physical reason for its outperformance is the ANN ability to avoid the oscillations and slow convergence characteristic of INC in these high-irradiance, rapidly changing conditions. By using the ANN in the specified range ( $1000\text{-}400 \text{ W/m}^2$ ), the proposed system ensures minimal energy loss during the tracking process that resulting in higher extracted power and a more stable response. This is further enhanced by the advanced boost VMS converter, which contributes to the overall higher power transfer and efficiency.

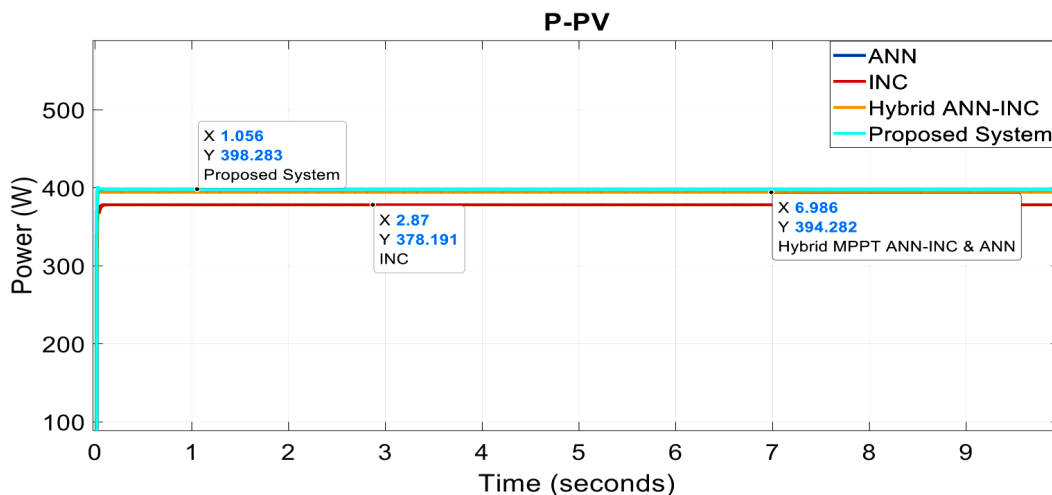


Fig. 10. MPPT's response to extracting MPP from a PV panel in  $1000 \text{ W/m}^2$

Fig. 11 shows the output power from the DC/DC converters at  $1000 \text{ W/m}^2$ . The proposed system consistently delivers the highest and most stable power to the load that reaching a maximum of  $375 \text{ W}$ . In comparison, the hybrid ANN-INC with a conventional boost converter provides a lower maximum output of  $370 \text{ W}$  while the conventional ANN and INC systems yield even lower and less stable output power. The superior effectiveness of the proposed system is a direct result of two key factors: the highly efficient MPPT and the advanced boost VMS converter. The hybrid ANN-INC MPPT guarantees that the photovoltaic (PV) panel is drawing as much power as possible, that minimizing energy loss at the source. The physical reason for the higher output power from the DC/DC converter, despite all systems attempting to extract maximum power from the PV panel, is that the conventional boost converter suffers from lower efficiency at high voltage gains. That is because it requires a high duty cycle which leading to increased switching and conduction losses. The advanced boost VMS converter, on the other hand, they are made to achieve a high voltage gain with a more moderate duty cycle, which that considerably lowers these losses and makes it possible for the extracted power to be transferred to the load more effectively.

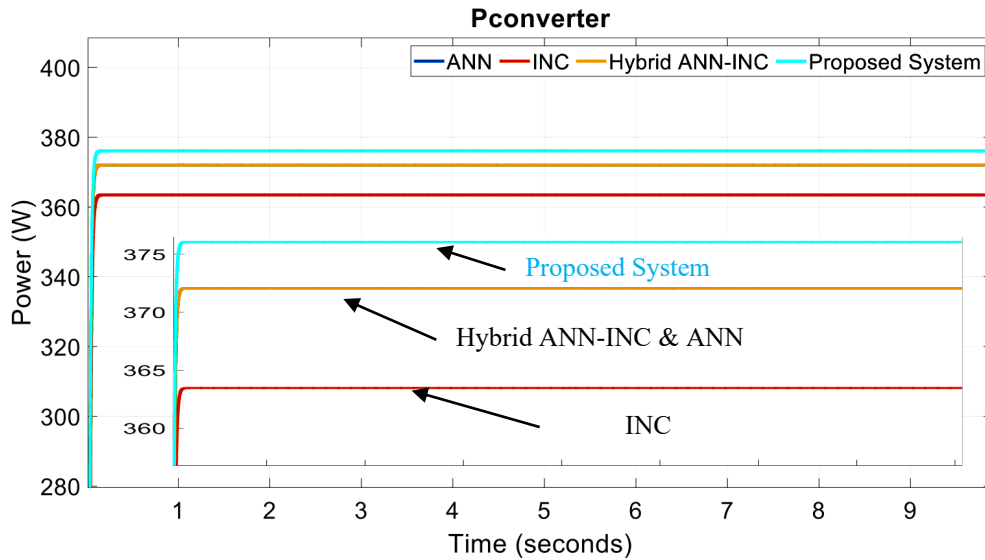


Fig. 11. Output Power from DC/DC Converters with maximum power point trackers

Fig. 12 shows the output current ( $I_{out}$ ) from DC/DC Converters with MPPTs. The proposed system (Hybrid ANN-INC MPPT + boost VMS converter) delivers the highest and most stable output current. At a high irradiance of  $1000 \text{ W/m}^2$ , the proposed system achieves a maximum output current of  $1.18 \text{ A}$  at approximately  $5.454 \text{ seconds}$ , maintaining a consistent current level throughout its operation. In contrast, the other systems demonstrate lower and more fluctuating output currents. For instance, the hybrid ANN-INC with a conventional boost converter reaches a maximum current of  $1.14 \text{ A}$  at a similar time, while the conventional ANN and INC systems yield even lower and less stable current outputs.

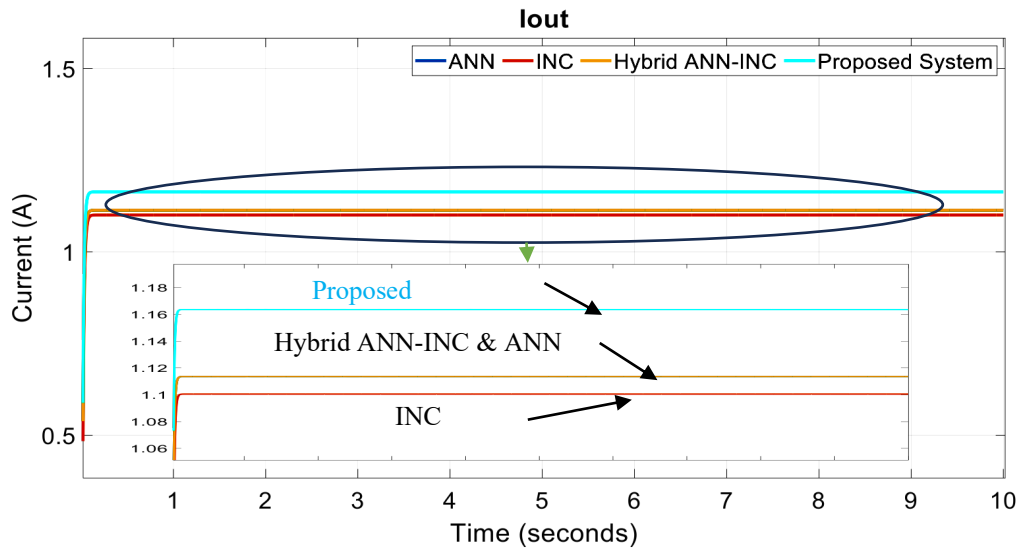


Fig. 12. Output Current ( $I_{out}$ ) from DC/DC Converters with maximum power point trackers

The superior performance of the proposed system in terms of the output current is a direct consequence of its enhanced efficiency in both power tracking and power conversion. The physical reason for this lies in the fundamental relationship between power, voltage and current ( $P=V \times I$ ). As previously established in the analysis the proposed system is capable of delivering the highest output power to the load. Since the output voltage of the DC/DC converter is regulated to a specific level a higher output power must be accompanied by a corresponding increase in the output current to satisfy the power equation. The advanced boost VMS converter plays a critical role in this

by minimizing conversion losses. In contrast to a traditional boost converter which increases switching and conduction losses by requiring an excessive duty cycle to obtain high voltage gain the VMS converter topology allows for a high voltage step up with higher efficiency. The reduction in the power loss during the conversion stage means that a greater portion of the power extracted from the PV panel is successfully transferred to the load that resulting in a higher output current. Consequently, the combination of a more effective MPPT algorithm and a highly efficient converter enables the proposed system to outperform its counterparts by delivering a higher current to the load.

Fig. 13 shows the efficiency of the power transfer from the PV panel to the load. The proposed system (Hybrid ANN-INC MPPT + boost VMS converter) demonstrates a clear and significant advantage over its counterparts. The proposed system reaches a peak efficiency of 93.911% at a rapid time of 1.748 seconds, a performance metric that is not matched by the other systems. The hybrid ANN-INC with a conventional boost converter achieves an efficiency of 92.9122% at a much later time of 5.878 seconds while the conventional INC and ANN systems yield even lower efficiencies of 90.7662% and 89.1662%, respectively at their respective convergence times.

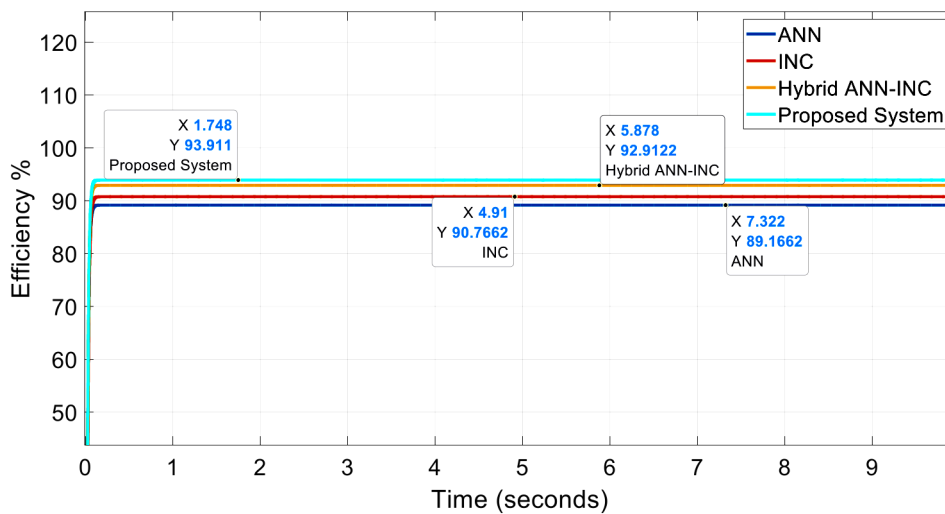


Fig. 13. Efficiency of the power transfer extracted from the PV panel

The profound physical reason for the proposed system superior efficiency is the synergistic operation of the two main components, the sophisticated hybrid MPPT algorithm and the advanced voltage multiplier stage (VMS) converter. The efficiency of a solar power system is fundamentally determined by the product of the MPPT tracking efficiency and the DC/DC converter conversion efficiency. The proposed hybrid MPPT algorithm intelligently switches between ANN and INC methods that ensure that the maximum available power from the PV panel is consistently and rapidly harvested under varying irradiance conditions. The optimized tracking minimizes the power loss at the source. Simultaneously the Boost VMS converter is engineered to overcome the inherent limitations of conventional boost converters which suffer from increased switching and conduction losses at high duty cycles required for large voltage step up. The VMS topology effectively achieves a high voltage gain with a lower duty cycle thereby drastically reducing these losses. Consequently, a greater percentage of the power extracted by the MPPT algorithm is successfully converted and delivered to the load. The dual pronged optimization efficient power extraction coupled with high efficiency power conversion is the physical reason that the proposed system outperforms the other configuration across all efficiency metrics.

The efficiency of MPP extraction is calculated as follows

$$Efficiency = \frac{Extracted\ Power}{MPP\ Power\ from\ PV} \times 100\% \quad (11)$$

### 3.2. Second Scenario Results

Fig. 14, which depicts the MPPT's response to extracting the maximum power at the irradiance level, provides compelling evidence for the superiority of the proposed system. Fig. 14 is critical because it captures the performance at the boundary condition where the Hybrid MPPT is still operating on its highly effective Artificial Neural Network (ANN) algorithm. You can clearly see that the proposed system—the Hybrid ANN-INC paired with the high-efficiency boost VMS converter—delivers the highest peak power and achieves the fastest convergence.

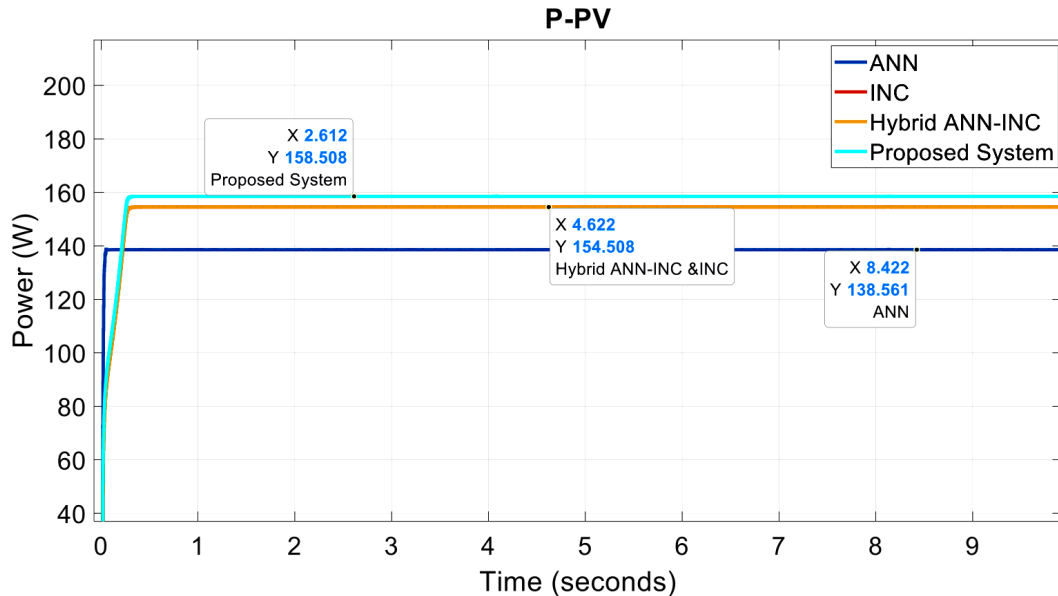


Fig. 14. MPPT's response to extracting the maximum power point from a PV panel in  $400 \text{ W/m}^2$

The proposed system hits its maximum power of at a remarkably swift time of . In stark contrast, the Hybrid ANN-INC system using the conventional boost converter—which should theoretically have the same MPPT tracking speed—reaches a lower maximum power of and takes longer to fully stabilize. The power difference and nearly faster response time for the proposed system are primarily due to a superior conversion efficiency of the boost VMS converter, which successfully transfers more of the power tracked by the ANN to the output without the high losses associated with the conventional converter at this operational point.

The slowest system is the conventional ANN-only configuration, which only manages and takes over to converge, while the standalone INC system shows similar slow behavior and power levels. This highlights that while the ANN is fast, the Hybrid ANN-INC strategy, even just the tracking part, has an edge, and combining it with the boost VMS power stage creates a system that is not only faster but also more powerful, proving the benefit of the dual-pronged optimization even at this mid-range irradiance level.

Fig. 15 shows how well the different DC/DC converters and MPPT configurations perform in terms of steady state output power when operating at  $400 \text{ W/m}^2$  of solar irradiation. The results presented unequivocally demonstrate the superior power delivery capability of the proposed system. The proposed system which that integrates the Hybrid ANN-INC MPPT with the advanced boost Voltage Multiplier Stage (VMS) converter, that achieves the highest sustained output power of 152.35 W. That represents a significant enhancement over the other configurations. In comparison the Hybrid ANN-INC MPPT when coupled with a conventional boost converter (denoted as "Hybrid ANN-INC & INC" in your provided values likely indicating the hybrid MPPT with a standard converter) yields an output power of 148.36 W. The difference of approximately 3.99 W underscores the enhanced conversion efficiency provided by the boost VMS converter even when paired with the same advanced MPPT algorithm. The VMS topology ability to achieve high voltage gain with reduced losses directly

translates to a greater transfer of an extracted power to the load. Furthermore, the conventional ANN MPPT system utilizing a standard boost converter, that delivers the lowest output power among the evaluated configurations, that stabilizing at 130.4 W. The substantial difference of approximately reach to 21.95 W between the proposed system and the conventional ANN configuration highlights the cumulative benefits derived from both the optimized hybrid MPPT strategy and the high efficiency boost VMS converter.

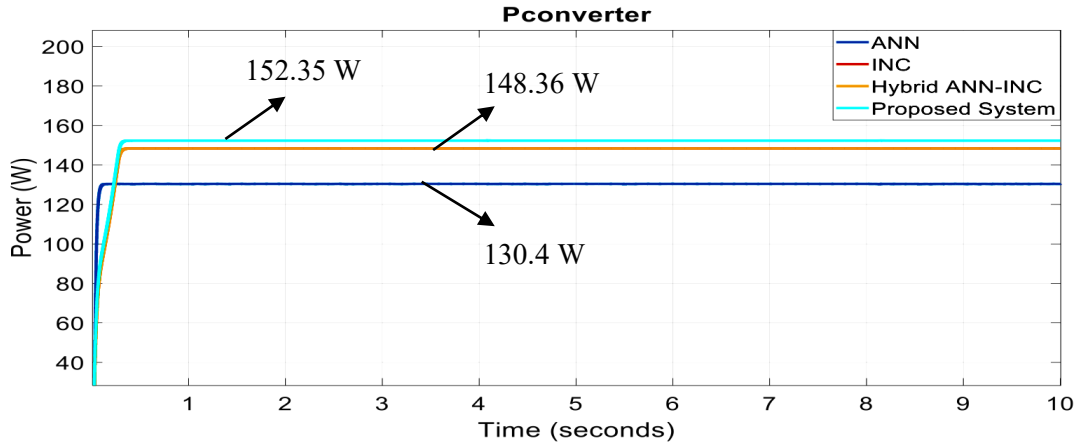


Fig. 15. The output power from DC-DC converters with maximum power point trackers

The superiority of the overall suggested system architecture is quantitatively supported by Fig. 16 which that show the efficiency of the power transfer extracted from the PV panel. The MPPT tracking efficiency multiplied by the DC/DC converter conversion efficiency is the primary determinant of solar power system efficiency.

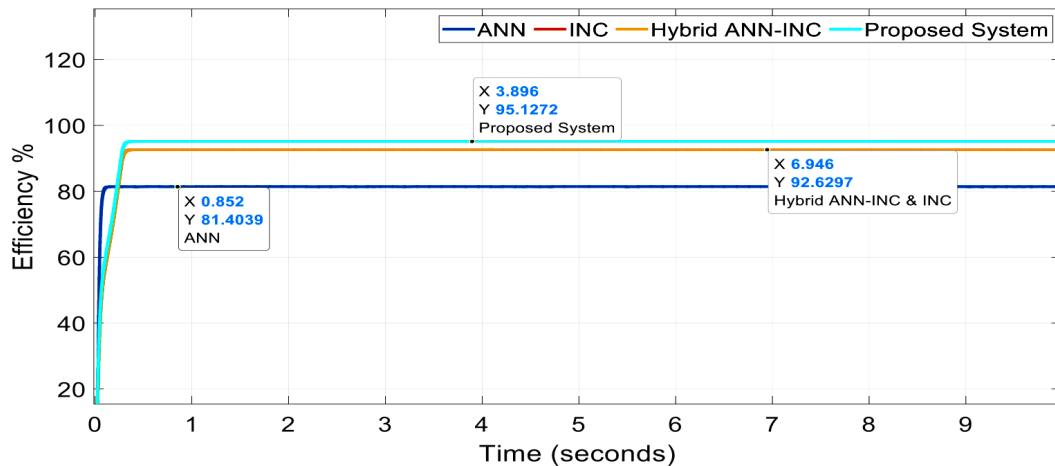


Fig. 16. Efficiency of the power transfer extracted from the PV panel

The proposed system (Hybrid ANN-INC MPPT + boost VMS converter) achieves the highest peak efficiency, that reaching 95%. That profound advantage is attributed to the synergy between the sophisticated hybrid MPPT algorithm and the advanced boost VMS converter. The Hybrid ANN-INC MPPT rapidly harvests the maximum available power due to the ANN predictive capability while the boost VMS converter overcomes the high duty cycle losses of conventional converters, that drastically reducing conversion losses.

Following the proposed system is the Hybrid ANN-INC algorithm when paired with a conventional boost converter which achieves an efficiency of 92% but stabilizes at a much later time of. That demonstrates that while the hybrid MPPT tracking is excellent the conventional converter limits the final realized efficiency due to its higher inherent losses.

The other systems show lower performance metrics. The conventional INC system yields an efficiency of 92%, and the conventional ANN system achieves the lowest efficiency at 81%. These lower figures for the individual MPPT controllers illustrate the benefit of the hybrid approach in achieving overall optimized tracking, which is then amplified by the high-efficiency conversion provided only by the boost VMS stage in the proposed system.

### 3.3. Third Scenario Results

Fig. 17 displays the MPPT response across a dynamically changing irradiance profile, specifically showing the transition from a high level ( $1000 \text{ W/m}^2$ ) down to the threshold of  $400 \text{ W/m}^2$  and subsequent system behavior. Fig. 17 illustrates the advantage of the intelligent Hybrid ANN-INC MPPT strategy and the superior power harvesting capability of the proposed system. At the initial high irradiance of  $1000 \text{ W/m}^2$  (implied by the initial high plateau), the proposed system demonstrates the fastest tracking speed, reaching its maximum power point at an extremely quick time of 1.056 s to achieve a maximum power of 394.28 W (as suggested by the results points in the zoomed region, although Fig. 17 labels are partially obscured, the context from other figures suggests the high-power plateau value)<sup>1</sup>. The convergence time of 1.056 s is significantly faster than the ANN system's 2.87 s convergence time at high irradiance, confirming the speed advantage of the hybrid approach in this regime, as the ANN part of the hybrid system is active<sup>2</sup>. The INC system lags considerably, reaching only 378.211 W at 1.252 s.

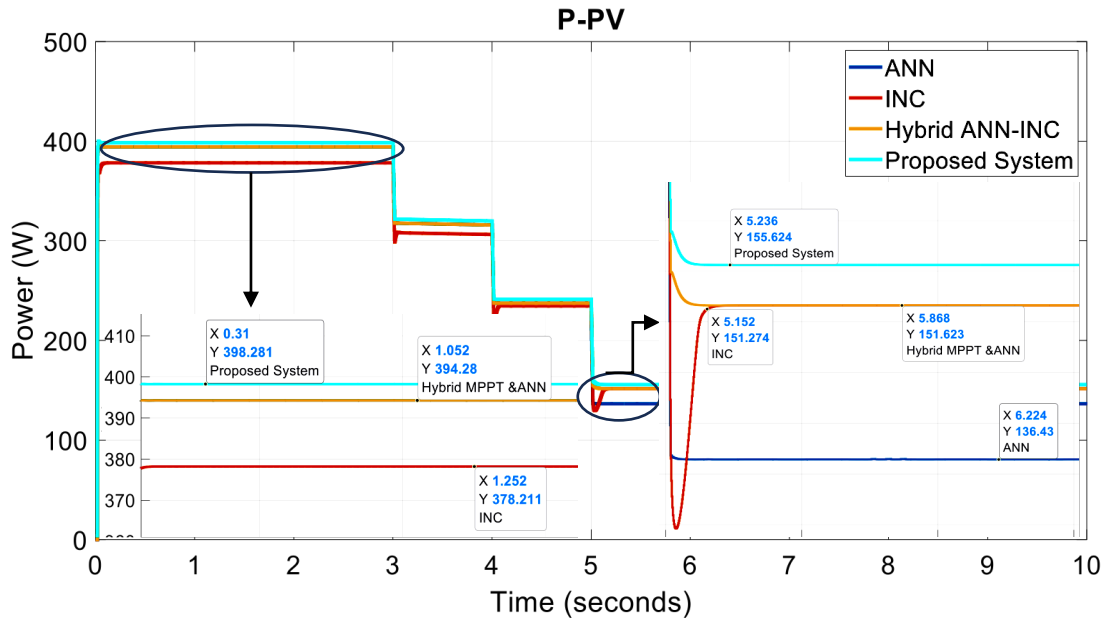


Fig. 17. MPPT's response to extracting maximum power point from a PV panel in  $1000\text{-}400 \text{ W/m}^2$

The critical observation is the system transition as irradiance drops. When the system experiences a sharp drop in irradiance (indicated by the subsequent transient dip), the proposed system exhibits superior stability and recovery. It is settling quickly to its new operating point. The Hybrid ANN-INC with the conventional converter shows a slower recovery and settles at a lower point 390.9 W at 5.868 s in the zoomed region) while the standalone ANN system experiences a much slower stabilization time of 6.224 s at a lower power of 136.43 W.

Most importantly when settling at the lower irradiance condition (implied by the later plateau, likely around  $400 \text{ W/m}^2$  based on the methodology) the proposed system sustains the highest power value of 155.624 W at 5.236 seconds. That is superior to the Hybrid ANN-INC conventional system 151.623 W and the standalone ANN system 136.43 W. This final steady state difference confirms that the boost VMS converter is crucial, that allowing the system to transfer the power efficiently even

when the MPPT switches to the INC algorithm regime below the 400 W/m<sup>2</sup> threshold, that resulting in the highest sustained output power.

Fig.18 illustrates the output power from the DC/DC converters across various MPPT strategies under changing irradiance conditions that providing a comprehensive comparative analysis of the proposed system against three conventional methods: ANN, INC and Hybrid ANN-INC. Initially, under high irradiance the proposed system achieves the highest output power of 383.208 W significantly outperforming the Hybrid ANN-INC & ANN combination at 355.343 W and the INC method at 349.549 W. That clearly indicates the superior performance of the proposed system advanced boost voltage multiplier stage (VMS) converter, which that efficiently maximizes power transfer even when the MPPT component (ANN) is shared with the conventional hybrid system. As irradiance drops to a moderate level the proposed system maintains its leading position with an output power of 150.564 W. The Hybrid ANN-INC & INC combination records 145.564 W while the ANN method yields 120.402 W. The performance at reduced irradiance further highlights the consistent power transfer efficiency of the proposed system, that demonstrating its robustness across varying environmental conditions.

Fig.18 also reveals the faster tracking capability of the proposed system. At the initial high irradiance, it reaches its maximum power within approximately to 2.41 seconds which is faster than the Hybrid ANN-INC & ANN and INC methods which take about 3.379 seconds and 3.398 seconds respectively. The rapid response minimizes energy loss during transitions and underscores the effectiveness of the hybrid ANN-INC MPPT in quickly converging to the maximum power point. The proposed system demonstrates superior stability and minimal power fluctuations as evidenced by the consistent power levels maintained after reaching the maximum power point. The output voltage and current have reduced total harmonic distortion (THD) as noted in the research, contributes to this stability, that ensuring a cleaner power output. The clear numerical advantage of the proposed system particularly its higher output power and faster tracking, that substantiates its overall enhancement in PV system performance compared to the conventional systems evaluated.

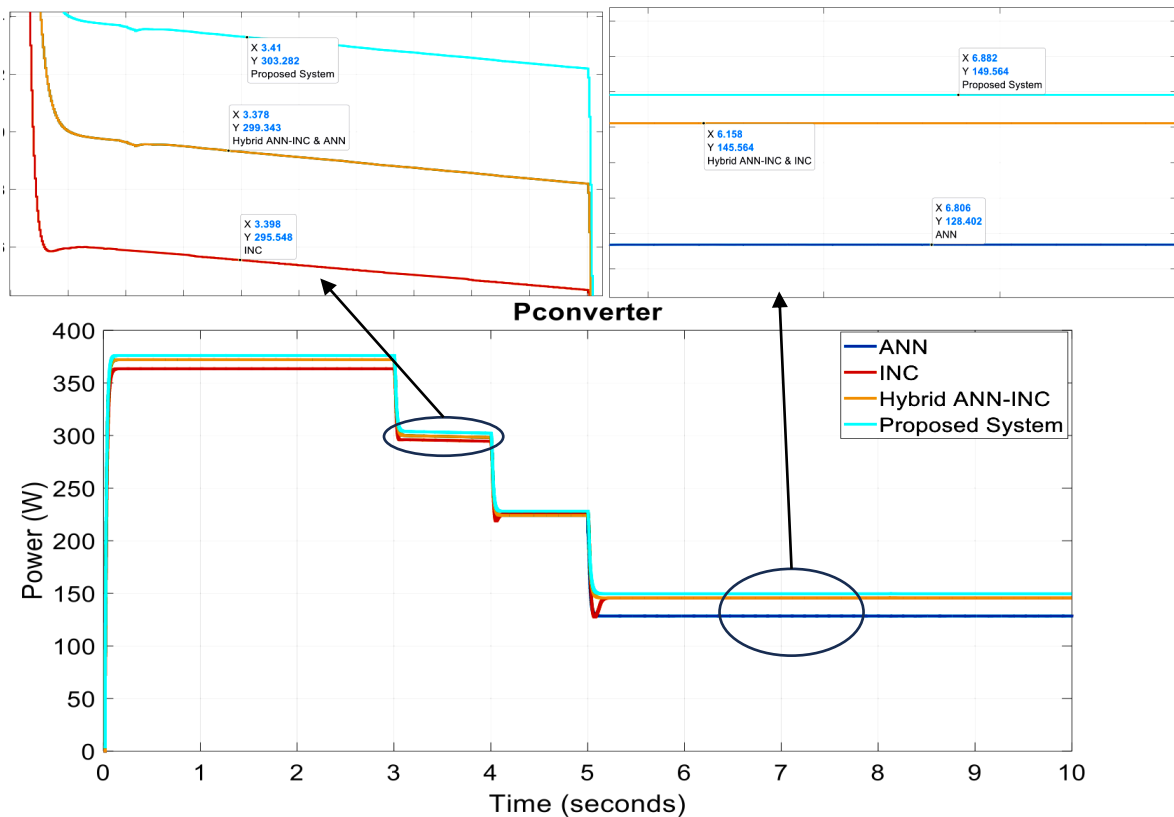


Fig. 18. The output power from DC-DC Converters with maximum power point trackers

Fig. 19, which illustrates the Efficiency of the power transfer extracted from the PV panel across a dynamically changing irradiance profile, provides compelling evidence of the superior performance of the proposed system. At the steady-state period under high irradiance (implied by the initial high plateau), the proposed system (Hybrid ANN-INC MPPT + boost VMS converter) achieves the highest efficiency of 93.3826%. This is notably superior to the Hybrid ANN-INC system (when paired with a conventional boost converter), which achieves a lower efficiency of 90.8851%. The lowest efficiency in this high irradiance regime is recorded by the ANN system at 80.1694%. This profound advantage is attributed to the synergy between the sophisticated hybrid MPPT algorithm for optimized power tracking and the advanced boost VMS converter, which overcomes the high-duty-cycle losses of conventional converters, drastically reducing conversion losses and maximizing the percentage of power successfully delivered to the load. The lower efficiency of the conventional hybrid system (Hybrid ANN-INC) demonstrates that while the hybrid MPPT tracking is excellent, the conventional converter limits the final realized efficiency due to its higher inherent losses. The lowest figure for the conventional ANN system illustrates the benefit of the hybrid approach in achieving overall optimized tracking.

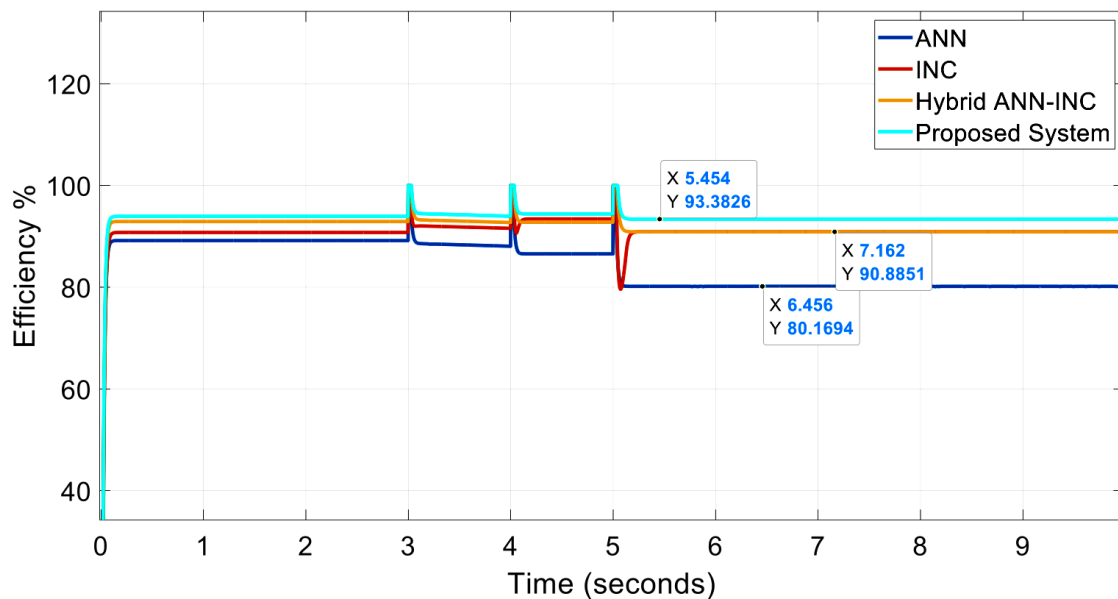
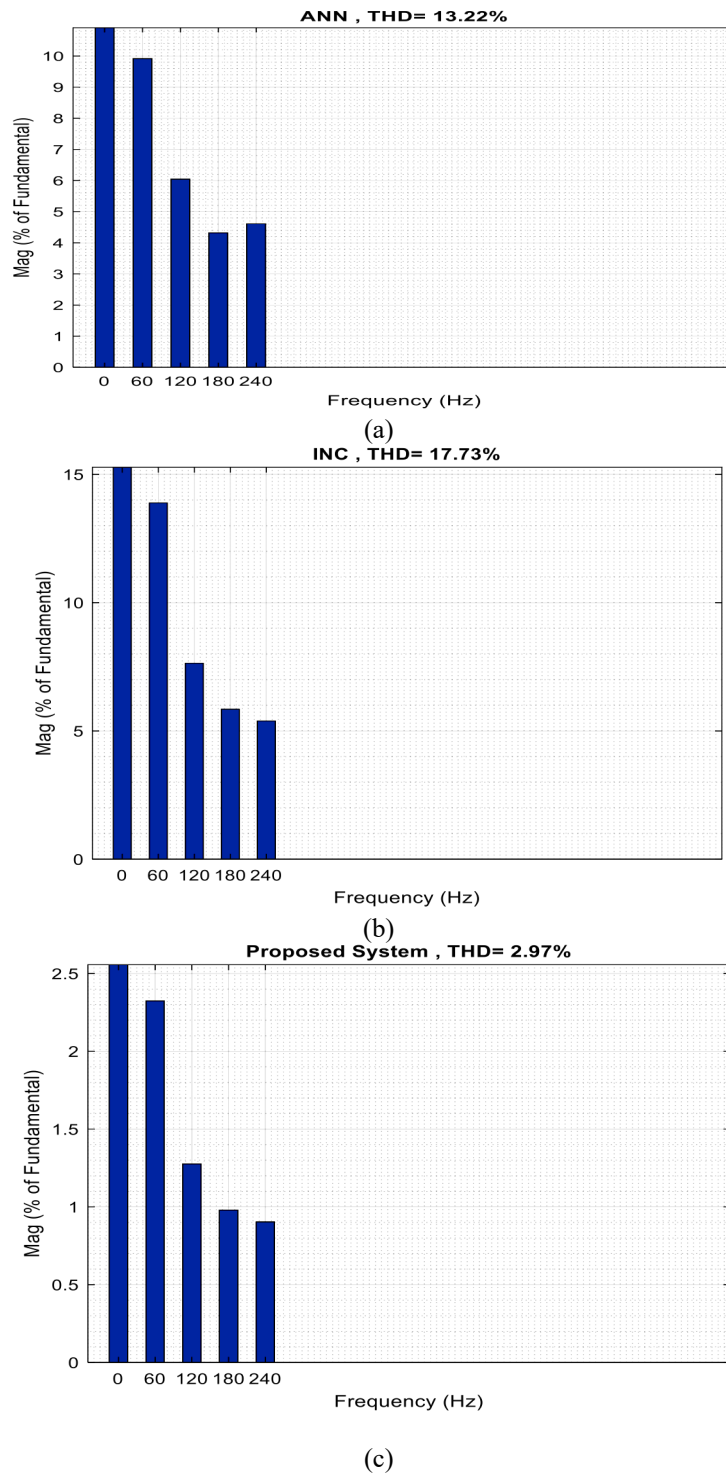


Fig. 19. Efficiency of the power transfer extracted from the PV panel

Fig. 20(a) corresponds to the ANN algorithm, which registers a THD of 13.22%. The major harmonic content after the fundamental frequency (implied at 60 Hz is evident at 120 Hz, representing approximately 6% of the fundamental, and at 180 Hz and 240 Hz which are both around 4% to 5% of the fundamental. Fig. 20(b) represents the INC algorithm, which exhibits the highest distortion with a THD of 17.73%. Similar to the ANN system, the dominant harmonic content is seen at 120 Hz, at a magnitude of over 7% of the fundamental, with the 180 Hz and 240 Hz harmonics also being significantly higher than those in the ANN system, over 5% of the fundamental. The higher THD in the INC system reflects the oscillatory and non-ideal tracking behavior characteristic of "hill-climbing" methods, which introduces more switching ripple and current distortion. Fig. 20(c) is for the proposed system (Hybrid ANN-INC MPPT + boost VMS converter), although the numerical THD value is 2.9%. The lowest THD, confirms that the proposed system delivers a cleaner output signal (lower THD) compared to the conventional boost converter. The combination of the optimal hybrid tracking strategy and the advanced boost VMS converter, which minimizes switching and conduction losses, results in a more stable and lower-ripple current. The overall research concludes that the proposed system secures the solution as the clear winner in every measured category, including lower THD of output current and voltage.

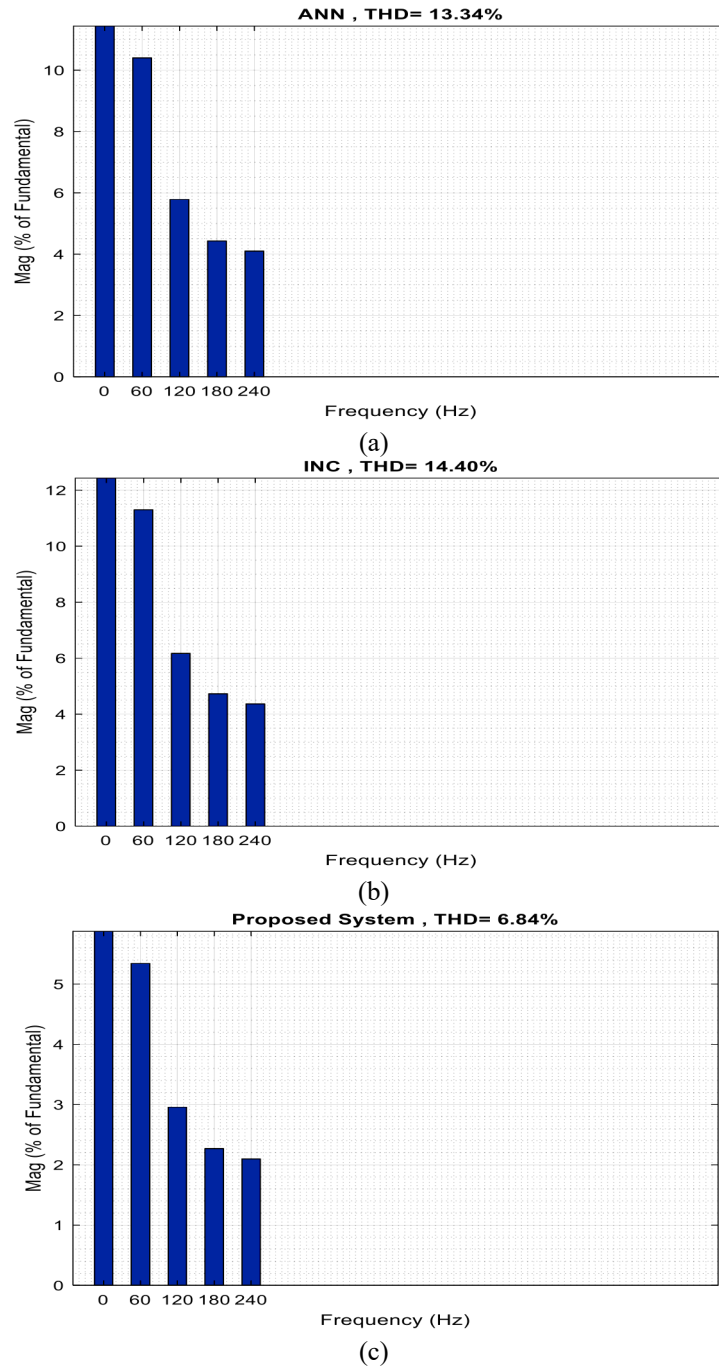


**Fig. 20.** THD of Output Current ( $I_{out}$ )

Fig. 21 THD of Output Voltage illustrate the significant improvement in voltage quality achieve by the proposed system compared to the conventional MPPT method. The proposed system demonstrates a clear and substantial advantage in minimizing harmonic distortion that registering the lowest THD value of 6.84%. The low THD value confirms that the combination of the Hybrid ANN-INC MPPT and the advanced boost VMS converter successfully deliver a cleaner and more stable output voltage. In contrast, the conventional MPPT systems us exhibit significantly higher distortion.

The ANN system records a THD of 13.34%. The INC system shows a slightly worse performance with a THD of 14.40%.

The superior performance of the proposed system (with a THD less than half of the conventional systems) is primarily a result for the boost VMS converter. The VMS topology is designed to achieve high voltage gain with a lower duty cycle which drastically reduces the switching ripple and noise inherent in the high duty cycle operation of conventional boost converters. The reduction in switching stress and associated losses translates directly into a much cleaner output signal that securing the proposed solution as the clear winner in power quality metrics.



**Fig. 21.** THD of output voltage ( $V_{out}$ ) of: (a) ANN; (b) INC; (c) Proposed System

**Table 4** shows Performance Comparison of MPPT and DC/DC Converter Configurations the arranges the key performance metrics of the proposed system against the three conventional configurations (ANN, INC and Hybrid ANN-INC all using a conventional boost converter).

**Table 4.** Performance comparison of MPPTs and DC-DC converter configurations.

MPPT Algorithm	Tracking Efficiency ( $\eta$ %)	Research Reference
Proposed Hybrid ANN-INC (High Irradiance)	93.911	Curren Research
Proposed Hybrid ANN-INC (Low Irradiance)	95	Current Research
P&O	97.6	El-Shimy, N. T. K. A., et al. [36]
PSO	90.3	El-Shimy, N. T. K. A., et al. [36]
Hybrid P&O-PSO	99.6	El-Sattar, M. M., et [37]
Hybrid ANN-P&O	98.93	Mitsuya, M. T., & de Moura Meneses, A. A. [38]
P&O-PGN	95	Yu [39]
ANFIS-MPPT-PI	96	Amara et al. [40]
P&O-fuzzy logic	82.13	Mahdi et al. [41]
P&O-Adaptive PI-Luo converter	96.8	Karrar Haider Tajaldin [42]

#### 4. Conclusion and Future Works

The research conclusively validated the efficacy of the proposed dual pronged optimization strategy that confirming that the synergy between the Hybrid ANN-INC Maximum Power Point Tracking (MPPT) algorithm and the advanced boost Voltage Multiplier Stage (VMS) converter results in a system that is superior to all conventional configurations. The results confirmed that simply using a smart MPPT is insufficient the true breakthrough lies in pairing the Hybrid ANN-INC tracking with the advanced boost VMS converter which collectively acts as a powerful efficient engine. Under high irradiance conditions the proposed system demonstrated ultra-fast convergence and the highest overall efficiency that reaching a peak of 93.911%. At moderate irradiance it sustained the highest power delivery and achieved an even higher peak efficiency of 95%. The performance is fundamentally rooted in the MPPT's ability to rapidly and accurately harvest maximum available power and the boost VMS converter ability to achieve high voltage gain with reduced duty cycle thereby minimizing the conversion losses that plague standard boost converters.

For future work, the research should focus on further enhancing the core components to push the performance envelope. Regarding the MPPT, future efforts should explore the implementation of a self-learning, adaptive deep learning network to replace the current pre-trained ANN, allowing the system to optimize its parameters autonomously in real-time and potentially eliminate the need for the discrete switching threshold by creating a unified, robust tracking mechanism that can handle both partial shading and rapidly changing irradiance with improved accuracy. In parallel, the DC/DC converter can be enhanced by investigating advanced wide-bandgap (WBG) semiconductor devices, such as Gallium Nitride (GaN) or Silicon Carbide (SiC) switches, within the boost VMS topology to further reduce switching losses and increase the switching frequency, which will lead to a more compact design and higher power density while pushing the overall conversion efficiency closer to 100%.

**Sustainable Development Goals:** This research can be categorized under Affordable and Clean Energy (SDG 7) and Industry, Innovation, and Infrastructure (SDG 9).

**Author Contribution:** All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

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