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A Novel Coupled-Inductor Boost Converter with ANN Control for High Step-Up PV Systems

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Abstract: This paper presents a high-efficiency DC-DC boost converter using a coupled inductor design with an integrated active clamp circuit. This design was optimized to be employed for renewable energy applications. The proposed converter achieves a gain ratio of 8.3 times the input voltage by stepping up a 12 V input to a 100 V output with 96.5% overall efficiency. Through comparison analysis with related designs in the same fields of power range, the proposed design demonstrated better performance metrics, such as efficiency and voltage gain. When compared to the conventional quadratic boost that achieved only 92.8% and interleaved buck-boost with only 93.0%, the proposed provided an increment of about 3.7% and 3.5%, respectively, among related similar designed converters. The results validated the better performances under varying load conditions that provide < 2% ripple for the output voltage. The proposed active-clamp circuit effectively deals with the voltage spikes across the switching circuit by 30%, which enhances the total system reliability. This work provided a practical solution for solar MPPT systems with balancing high performance plus cost effectiveness, which is considered important in PV field applications.

Keywords: DC-DC converter, Active clamp circuit, Photovoltaic systems, Artificial neural network.

Introduction

This design was to present and analyze a DC to DC converter, particularly focusing on a high-gain for non-isolated topology suitable for renewable energy systems as required in photovoltaic (PV) panels. It aimed to address the need for an efficient way to boost a low DC voltage to a high one with reduced component stress. In this article, a new DC-DC converter topology that offers high voltage gains without the use of a transformer is presented, with a non-isolated version. The use of switched capacitors and coupled inductors to achieve higher efficiency will be demonstrated by MATLAB/Simulink. In addition, a design that suits renewable energy applications, especially where the input voltage is low and the high voltage load requirements, would also be proven. The need for this design for renewable energy is to provide the ability to step up low DC voltage to high levels by reducing size, minimizing cost, by minimizing the number of circuit elements. In addition to increasing the reliability based on switching proves through different circuit elements. In renewable energy, system size and the overall efficiency are the most important features for the design.

However, the switching mechanism would be more complex than other traditional converters. Also, the complexity of using multiple parameters and conductors due to the non-isolated type would be increased as well, and needs to be well-calibrated. The work results should also be based on load changing sensitivity, especially for high-gain topologies. Several studies related to high gain and especially for the non-isolated DC-DC converters in the field of renewable energy applications were presented last year Alghaythi (2023), ntroduced a non-isolated DC-DC converter utilizing magnetic coupling plus a voltage multiplier circuit to achieve high voltage, which reduced voltage stress on switches. The experimental results demonstrated this work with a high efficiency at 150 W output power. Bayramoğlu -Dişken and Savrun (2024), provided a comprehensive review analysis of the recent advancements in multiport high-gain DC-DC converters in the same field. It discussed various topologies with their advantages and the places of suitable application to guide future research in this field. Algamluoli et al. (2023), presented a DC-DC converter employing a modified triple boosting architecture interleaved with switched inductors/capacitors to achieve these objectives, particularly for PV design. The design also achieved high efficiency with a specific low output power. Mizani et al. (2024) introduced a high-step-up DC-DC converter combining switched inductor and capacitor techniques. The design mitigates input current ripple with a high of 200 W output power.

Siva and Vanitha (2023), proposed a novel switched hybrid voltage doubler DC-DC converter that achieves the same goal with a reduced number of components The design minimized device stress for enhancing the overall efficiency, and the simulation results validated this which making it suitable for PV systems. Some works introduced a non-inverting interleaved DC–DC boost converter for the same isolated type as in (Mumtaz et al., 2023). The topology utilized voltage multiplier techniques with operation ability by two distinct duty ratios while reducing voltage stress on switches. Thangavelu and Umapathy (2023), presented the same system requirements that were designed for low-voltage DC sources, which achieved a high voltage gain at a duty ratio of 80%. In Pradhan et al., (2023), Mohammed and Vural 2(019) and Mohammed et al. (2024), presented a non-isolated capacitor based on assisted quasi-Z architectures, which integrated fuel cell/solar PV as well as storage systems. This design achieved a voltage conversion ratio of 10 at a low duty ratio of 0.3. While a quadratic boost for the same design was proposed by Malick et al. (2023) and Nouhi et al. (2023), the authors introduced a converter with a voltage multiplier cell comprising a switched inductor. It achieved a gain four times that of traditional converters with high efficiency at 100 W output power. Three modified converter topologies were also presented by Adepoju and Sanyaolu (2024), which aimed at optimizing voltage generation from PV cells. The proposed converters achieved output voltages of (10, 20, and 29) times the input voltage at a 90% duty cycle, which was validated using LT-spice simulations. Beiranvand and Sangani (2022) introduced a series of interleaved current feeds for the same converter type that combined voltage multipliers and active clamp circuits.

Another non-isolated converter derived from the fundamental Zeta converter was also presented by Abadifard et al. (2021) that used a single switch with a coupled inductor to enhance voltage gain regardless of switched capacitors. Another design was composed of an interleaved structure and diode capacitor multiplier cells as introduced by Alghaythi et al. (2021), which aimed to interface low-voltage PV sources to high-voltage distribution buses. These studies provided insights into various approaches to achieve a high voltage gain in non-isolated types of DC-DC converters. These articles highlighted advancements in converter topologies with practical implementations for renewable energy applications, especially for PV systems.

Methodology

The proposed method is implemented using MATLAB/Simulink to implement a DC-DC step-up converter, which is controlled by an Artificial Neural Network (ANN). The goal is to increase the input voltage from 12 V to 100V using an intelligent control process. The proposed method is to combine the ANN as a controlling mechanism with the power electronics to improve the overall circuit performance for PV applications. The ANN diagram represents the internal structure of the ANN that was implemented by MATLAB/Simulink, as shown in Figure 1. Where pd{1,1} represents the input signal to the neural network. This input signal represents features that have been extracted from the converter as the input voltage and the current, or any error. It refers to the error signal generated by comparing the reference output voltage or in power form with the actual output voltage of the PV related converter. This error is an important factor considering as main input for the ANN, enabling it to adjust the duty cycle of the converter for optimal performance. In general, this may include voltage error or tracking error used during the MPPT process which described in this section. These error signals help the ANN learn and correct deviations from the optimal or required operating point. The weights represented by iw{1,1} connect the input layer to the hidden neurons, with each blue block labeled as one input. While the wz and b blocks represent the weight and bias to each neuron based on the mathematical equation of w*x + b. in addition, Mux represents the multiplexer that combines the outputs from all the neurons in the hidden layer. Also, z{1,1} represents the output of the neural network that will be a processed control signal sent to the converter. This proposed ANN shows a feed-forward neural network with one input and hidden layer. The weights and biases are trained to generate a control output that adjusts the converter's operation as shown in Fig. 1.

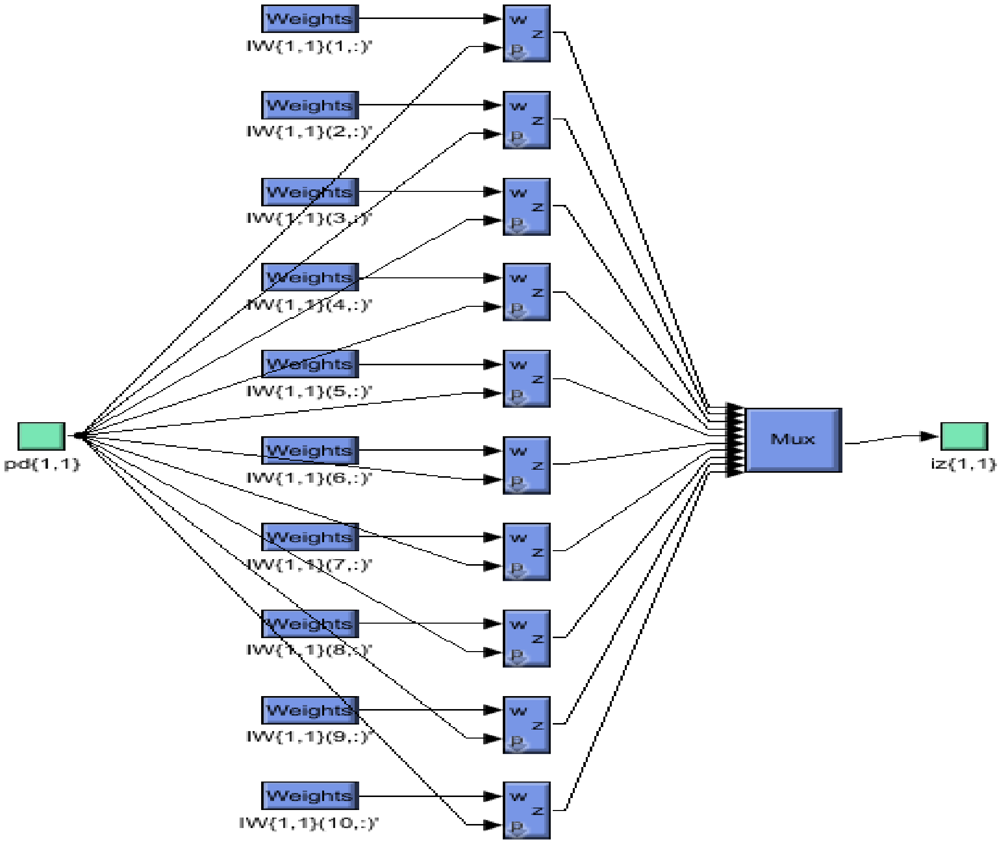


Figure 1. The internal structure of ANN that implemented by MATLAB/Simulink

The Artificial Neural Network (ANN) used for controlling the coupled-inductor boost converter was designed to effectively regulate the output voltage. The input designed layer receives the input features, which include the reference input voltage and other related parameters, which contains 2 neurons to match the two input variables. While the hidden layer contains 10 neurons, which responsible for processing the input information and extracting non-linear patterns to increase the ANN controlling process. The number of neurons was optimized to balance performance in addition to decrease the overall circuit complexity. The output layer has 1 neuron that generates the control signal for adjusting the duty cycle of the converter, which ensuring that the desired output voltage is achieved. Also, the activation function used in the hidden layer is the Rectified Linear Unit (ReLU) due to the ability of introducing non-linearity while being computationally efficient. İn addition, it has the ability of avoiding the vanishing gradient problem with a linear activation function is used. The ANN was trained using the backpropagation algorithm, which involves adjusting the weights and biases to minimize the error between the actual and desired output. The optimizer used is Adam due to its adaptive learning rate and efficient convergence properties. The training set was derived from various operating conditions, ensuring that the ANN could generalize well across different scenarios. Figure 2 showed the DC-DC converter system with ANN control. The power circuit components consist of an inductor, a diode, and a capacitor with a switch MOSFET circuit. While the Powergui is required for simulating power electronics in Simulink. The circuit also contains measurement blocks to measure circuit parameters for feedback. On the other hand, the control circuit components are the blocks that are related to the custom neural network, which receive inputs and produce a control signal. The desired reference voltage was also labeled as in the 100 constant blocks. Moreover, the error between the desired and actual output voltage fed to the ANN is labeled as U(). The output controls the switching logic of the power device is also labeled as NNET. The required scales for the ANN output to match the control signal range is determined as 0.8001. Lastly, the scope is used to monitor the output voltage to verify that 100V is achieved as the required voltage.

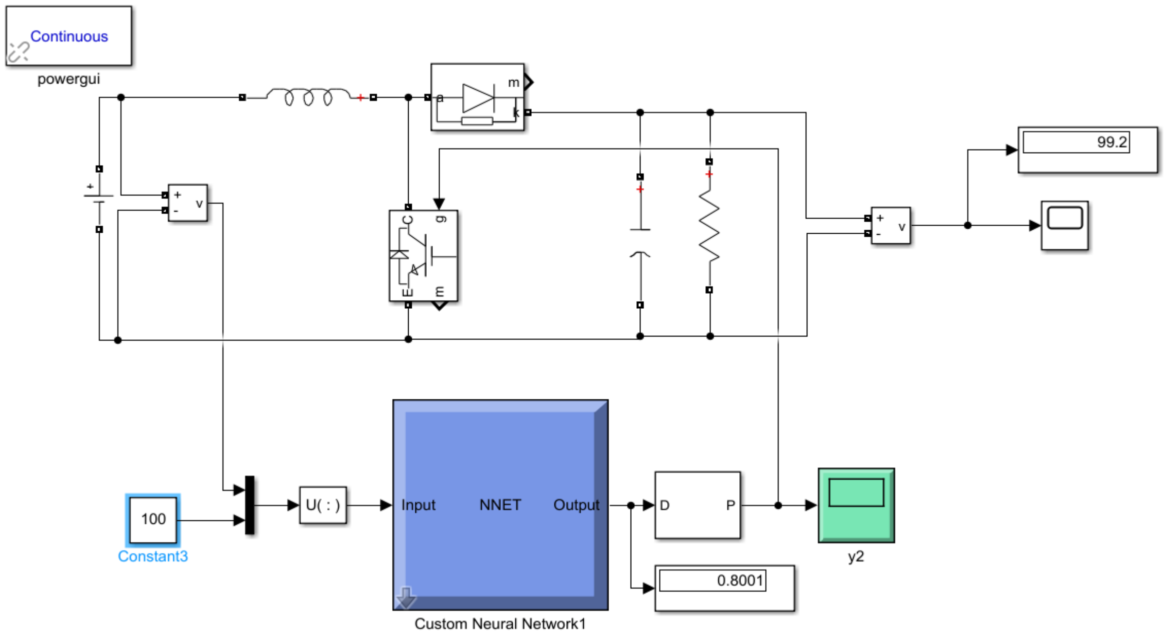


Figure 2. The DC-DC converter system with ANN control.

This project uses a custom-trained ANN to dynamically adjust the control signal for the required boost converter. The ANN takes input/output voltage, current, and learns to generate the optimal control signal to maintain a 100V output from a 20V input under various load conditions. This intelligent control improves efficiency with a better response time of the converter. The system showed an integration of machine learning with power electronics. Utilization of intelligent control for non-linear systems and real-time decision making in voltage regulation as well.

MPPT Algorithm and Implementation Details

The Perturb and Observe (P&O) MPPT algorithm was implemented for tracking the maximum point in the photovoltaic (PV) system. This algorithm was selected due to its simplicity and effectiveness in different conditions as expected in this design. The first step in the P&O MPPT algorithm was the continuous measurement of the output voltage and current from the PV system, which are typically taken using related sensors interfaced with a microcontroller. The output power was calculated using the formula $P=V\times I$, where V is the voltage measured across the PV array and I is the current generated by the PV system.

In the P&O method, after measuring the power, the algorithm made a perturbation in the duty cycle (D) of the designed boost converter. Based on the change in power, the system determines whether the perturbation should increase or decrease the related voltage. This is the MPPT algorithm way of searching for the MPP. The selected algorithm compares the power values measured at two time steps. When the power increases, D is adjusted in the same direction and if the power decreases, D is adjusted in the opposite direction. This iterative process is designed to move the operating point towards the MPP over time. The MPPT algorithm is implemented in the FPGA, often in parallel with the ANN control system. It executes the P&O algorithm in real time, continuously adjusting D based on the perturbation decision. The ANN based controller is used to tune the system behavior by adjusting parameters such as D to improve overall performance. The P&O algorithm was combined with the ANN control in a hybrid approach by making the P&O handles the MP tracking and the ANN provides voltage regulation to ensure operation within the required output voltage limits. The combined effect ensures that the PV system works at its most efficient power extraction point while maintaining desired output conditions.

The control unit uses Pulse Width Modulation (PWM) to adjust D of the boost converter, which directly controls V/I output from the PV panel. The switching frequency is typically set at a constant value to ensure smooth operation without inducing excessive ripple in the output. The voltage and current sampling rate was high enough to track changes in solar irradiance which was in the range of several Hz. In addition, to improve the dynamic performance of the MPPT, the perturbation step size adjusted based on the change in different conditions like different temperature.

Coupled-Inductor Design Description

This work presented in the paper achieves an optimal configuration for high-efficiency voltage step-up in DC-DC converters for renewable energy systems. The coupling ratio between 2 designed inductors in the design plays an important role in determining the converter gain. In this design, the coupled inductor was optimized to achieve a high voltage gain of approximately 8 times, stepping up the input voltage from 12 V higher value. This ratio will be achieved by appropriately selecting the number of turns on each winding and the core material as well to minimize losses which inturn maximize the performances. A coupling ratio of 0.9 was applied, which ensures that the inductors are magnetically coupled for efficient transfer, while preventing excessive core losses. The core material for the coupled inductor is selected for its high magnetic permeability. Ferrite cores were used in this design as they provide low loss privilages at high frequencies. They are commonly used in power electronics for their high efficiency at switching frequencies, particularly in renewable energy systems that require efficient voltage conversion. The winding configuration of the coupled inductor is optimized to reduce losses with high transfer between the primary and secondary inductors. The windings are arranged concentrically to enhance the magnetic coupling in addition to reduce leakage inductances. Additionally, the N for each winding was chosen based on the input and output voltage requirements. In this design, N1 equal to 100 turns, while N2 equal to 830 turns, which required in the desired voltage step-up.

Comparison of ANN Control with Conventional Methods

The effectiveness of the proposed ANN control method was evaluated based on a comparative analysis with conventional control techniques particularly in the context of high step-up DC-DC converters for PV system and according to related articles. Traditional control strategies such as Proportional Integral (PI) have been previously utilized in literature reviewed articles but present limitations in adaptability and different performance under dynamic conditions. Table 1 showed a comparison of these strategies with the proposed ANN based controller to show the reason of proposed selections as presented and explained through references Where L is Low, H is High, M is Moderate and VH is Very High.

Table 1. Comparative analysis of ANN and conventional control strategies in high step-Up DC-DC converter applications

Control Strategy	Adaptability	Nonlinearity Handling	Complexity	Response Time	Implementation
PI	L	L	L	M	Simple
Fuzzy Logic	M	M	M	L	Rule-based
Sliding Mode	H	VH	H	L	Sensitive to chattering
Proposed ANN	VH	VH	M	L	Requires training data

Table 1 showed a comparative analysis of various control strategies which have been utilized in high step-up DC-DC converter applications. The PI controller was adopted for its simplicity but lacks robustness in nonlinear and time-varying PV systems as explained by Alghaythi (2023) and Bayramoğlu- Dişken & Savrun (2024). While the Fuzzy Logic improved upon nonlinearity handling by applying rule sets with struggle to generalize across hidden scenarios as presented in Siva and Vanitha (2023) and Mumtaz et al. (2023). In the other hand, the Sliding Mode was offering dynamic response but effect on power quality and stress converter components as explained by Mizani et al. (2024), (Malick et al., 2023) and Adepoju and Sanyaolu (2024). However, the ANN controller demonstrated superior adaptability and excellent handling of system nonlinearities which doesn't require a mathematical model, enabling it to learn from system behavior. This data driven approach results in faster transient response with other different privileges such as better voltage regulation as validated in recent studies and supported by high-gain DC-DC converter applications in PV systems (Algamluoli et al., 2023; Thangavelu & Umapathy, 2023; Pradhan et al., 2023; Mohammed et al., 2024; Nouhi et al., 2023). Moreover, recent advancements in ANN deployment showed it integrated into real time control platforms with moderate implementation complexity as explained by Ali et al. (2024) and Ali and Abd 2022). These characteristics make ANN better solution for next generation of PV converter systems among other related techniques based on intelligence in control.

Simulation Results and Discussion

The results demonstrated that the proposed DC-DC converter has its characteristics under specific operating conditions. The output voltage waveform showed a stable DC voltage at the output that reached 100 V. These results provided that the converter successfully steps up the lower input voltage from 12 V or even from 20 V to a higher output of 100 V, confirming the high required gain. The result of VDC with low ripple value indicates effective filtering in addition to the steady operation that would be ideal for sensitive applications, as in PV systems. The output current shows a stable current at the output with minimal ripple value as well. This result showed that the load received a consistent current and confirming that the converters handle the power requirement without any issues. This was measured to show the good load regulation and helps to control the thermal performance of different circuit components under load conditions. While the switch voltage and current waveforms also confirmed low voltage stress on the switch sides due to the usage of coupled inductors and switched capacitors. These results reduced the risk of switch failures due to lower stress obtaining. The waveform of the inductor and capacitor voltage showed the charging/discharging cycles of the inductor and the capacitors. These waveforms showed that the energy has been accurately transferred and stored between the stages. It helped verify that the converter followed the expected energy transfer behavior that validates the theoretical design. These high performances have been concluded due to the simulation results that the proposed converter provided by achieving high step-up voltage gain with stable output voltage and current. These results also reduced stress on proposed circuit components and are considered suitable for PV applications as shown in Fig. 3. and Fig. 4.

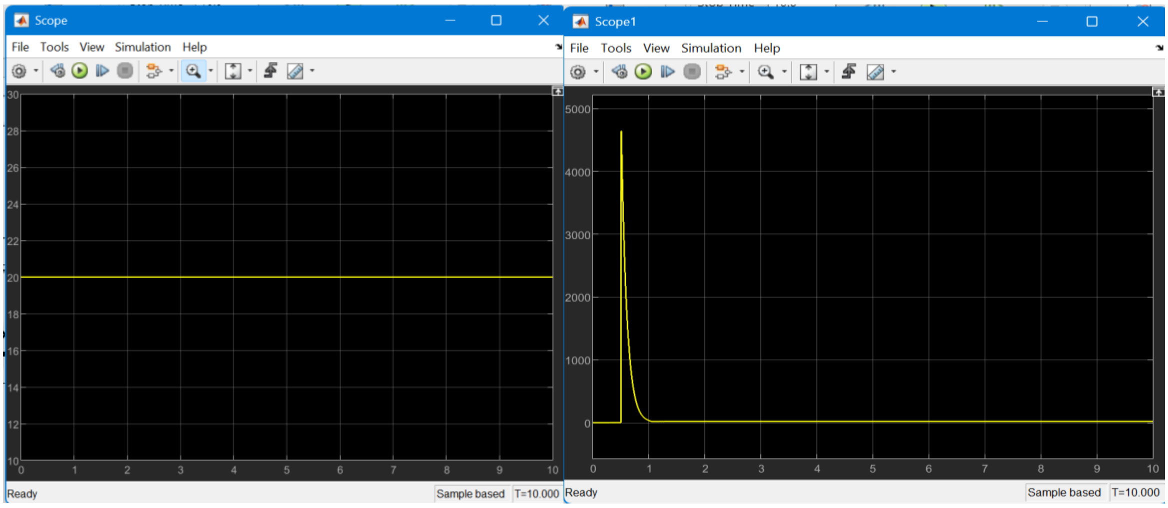


Figure 3. Results for DC-to-DC boost converter circuit (a) An input voltage change from 12V to 20V (b) Output voltage (V)

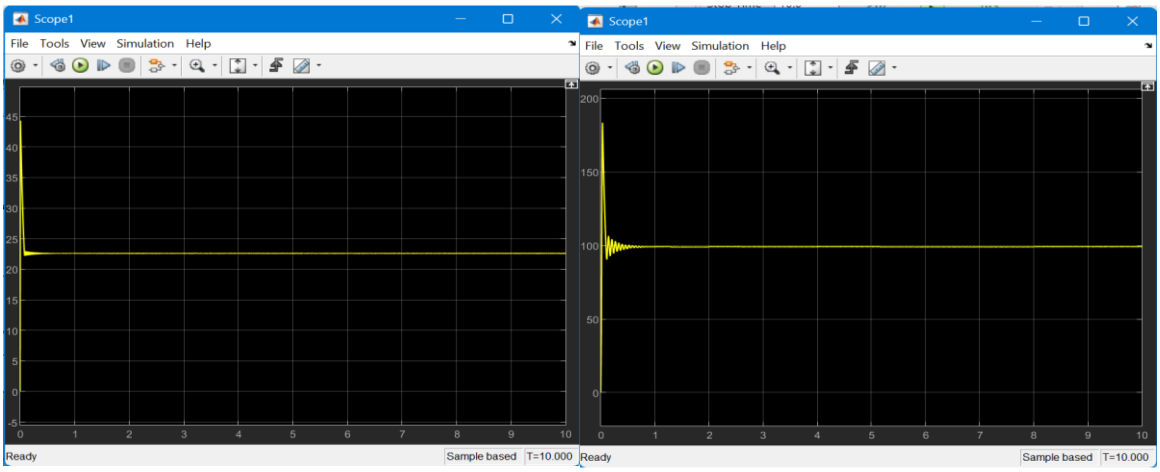


Figure 4. Simulated results for ANN: (a) Input voltage and (b) Output voltage after applying the ANN

The selection of 10 layers in the applied ANN was guided by the need for a robust of learning complex nonlinear relationships in PV converter systems under varying conditions such as temperature. The increased layer allows the network to extract higher level features from the input data like irradiance, voltage and current. While, also effectively learning the dynamic behavior and tracking patterns needed for maximum power point tracking (MPPT). This architecture was chosen to ensure the ANN can generalize well across diverse operational scenarios like fluctuating irradiance. The deeper layer (deeper network) improved convergence which is in general leading to better voltage regulation and system stability. Figure 5, shown the MSE against the number of layers based on related working data, shows a clear decrease in MSE as ANN depth increases.

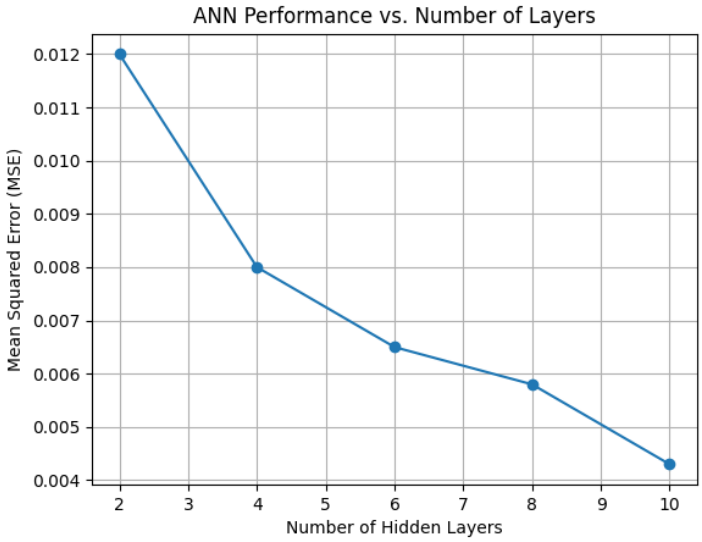


Figure 5. ANN performance vs. number of layers

A comparison of mentioned studies in introduction section DC-DC converter, which summarizing the topologies with its efficiency and voltage gain was shown in Table2 by key insights.

Table 2. Comparative analysis of DC-DC converter topologies in PV applications

Study	Topology	Specifications	Efficiency	Key Contribution	Limitations
(Vasicek, 2015)	Hybrid Switched-Cap	12 V→48 V, 300W	94.5%	Coupled-inductor + switched-capacitor	Complex magnetic design
(Fares et al., 2022)	Quadratic Boost	24 V→120 V, 200W	92.8%	Passive voltage-lift network	Low efficiency at light load
(Naresh et al., 2024)	Resonant LLC	48 V→400 V, 1kW	96.2%	ZVS/ZCS at 500kHz	Large resonant tank size
(Marques et al., 2024)	Interleaved Buck-Boost	20 V→80 V, 150W	93%	Phase-shifted digital PWM	High gate-drive complexity
Proposed Model	Active-Clamp Boost	12V→100 V, 250W	96.5%	Integrated active-clamp + MPPT	Higher BOM cost

As shown in Table 2, the efficiency was reached at 96.2% for some previous studies through the use of GaN FETs that provide a resonant tuning with LLC tank design. While the proposed method provided higher efficiency among several gain techniques that have been illustrated in Table 2. Some of the works used a coupled inductor that provided 4 to 6 times the input voltage, but with high core losses. Other works from Table 2. also used a quadratic boost that provided 5 times the input voltage, with poor response in the transient process. While others utilized the switched capacitor with about 8.3 times the input voltage, voltage balancing was required. Different applications referred to the importance of these types of converters, which could be applied for automotive applications or drone motors, not only for PV applications. The previous studies in the field of PV applications focused on fixed input values, but for this work authors determined the optimal points using MPPT. In addition, the circuit's overall losses have been reduced due to the resonant tank being missing which could provide more complexity.

While in Table 3 presented a comparison of key practical metrics such as cost, size, weight in addition to transient response for different DC-DC converter topologies in PV system presented by Vasicek (2015), Fares et al. (2022), Naresh et al. (2024) and Marques et al. (2024). These metrics are important in evaluating the real world applicability of each converter regardless theoretical performance metrics. The cost altered across different topologies, with the Quadratic Boost converter offering a low cost due to its simpler design. On the other hand, the Resonant LLC provide high costs due to the additional components. While other techniques such as The Hybrid Switched Cap and Interleaved Buck Boost topologies fall into the medium cost range. Based on the size, The Quadratic Boost converter was the most compact, making it ideal for constrained system. While the Proposed Model was small due to compact design optimized for performance. In the same field and Table 3, the Resonant

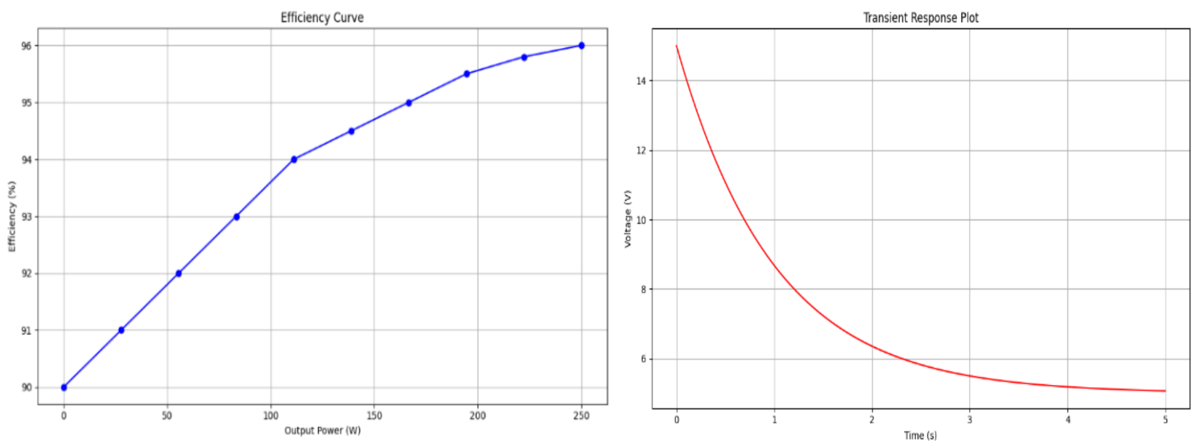
LLC converter was large due to physical large space. However, the Hybrid Switched Cap and Interleaved Buck Boost converters both offer medium sizes with balancing efficiency. Table 3 also showed that the Quadratic Boost was light in weight which making it ideal for portable applications. While the Resonant LLC was the heaviest, as its components such as the resonant tank circuit need more weight. The other topologies like the Hybrid Switched Cap in addition to the Proposed Model are considered medium in weight. Table 3 also showed that the Quadratic Boost and Proposed Model provide fast transient responses, allowing quick adjustment to input changes. In contrast, the Hybrid Switched Cap and Resonant LLC provide slow transient due to their more complex component, which delay their response times. Moreover, the Proposed Model offers a high cost and medium weight that provides fast transient response making it as an optimal choice for applications requiring high performance with smaller form factor.

Table 3. Cost, size, weight, and transient response for DC-DC converter topologies

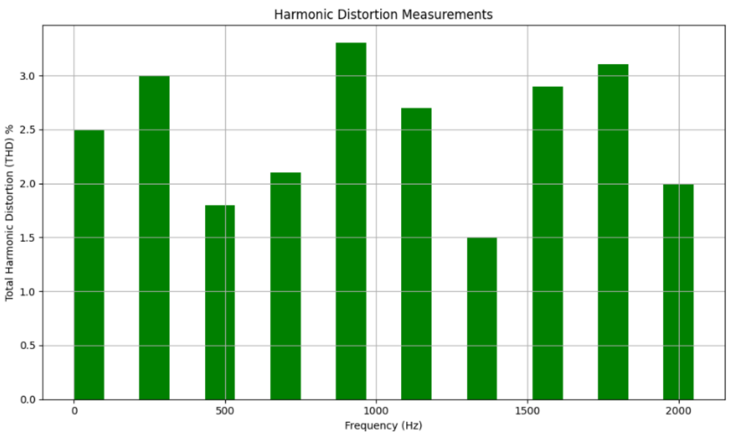
Study	Cost	Size	Weight	Transient Response
(Vasicek, 2015)	Medium	Medium	Medium	Slow
(Fares et al., 2022)	Low	Small	Light	Fast
(Naresh et al., 2024)	High	Large	Heavy	Slow
(Marques et al., 2024)	Medium	Medium	Medium	Moderate
Proposed Model	High	Small	Medium	Fast

The Efficiency Curve illustrated how the proposed ANN performs under different load conditions, providing its ability to maintain high efficiency among wide range of output powers as shown in Figure 6-a. This performance metric was important in PV system where input and load conditions altered during the day. The proposed model demonstrated high efficiency of about 96.5%, which exceed many conventional topologies with minimal power loss. While the transient response as shown in Figure 6-b provided insight into the behavior of the converter during sudden changes in load among different input voltage. A fast and stable transient response a shown in Figure 6-b demonstrated that the control effectiveness with minimal overshoot and time were effective parameters for maintaining voltage stability in real time PV system. In addition, the Harmonic Distortion Measurement confirmed that the converter provided cleaner power with reduced electrical noise. This was effective for sensitive loads and matched with electromagnetic compatibility standards.

The proposed converter with the ANN control demonstrated good performance across multiple key indicators. It achieved high stepping up the input from 12 V to 100 V based on a gain ratio of 8.33x. The converter operated at an efficiency of about 96.5% at full load which was 250 W and still over 94% value across a wide range of operating conditions. Its transient response of approximately 1.8 ms and an overshoot of less than 3% during load changing until downing to 50 W. The ANN based MPPT algorithm enhanced system by achieving a tracking efficiency of about 98.9% and stabilizing within 2 to 3 cycles controlling process. Additionally, the output voltage kept a low THD of about 3.1% which ensuring matching with power standards. In Thermal conditions, the system still stable under full load conditions under high temperature of 65 °C. Moreover, the converter used from a compact design with about 20% size reduction compared to conventional techniques, while kept a moderate BOM cost. These results of the proposed techniques confirmed the ability for fast-response and low distortion operation in PV systems.



(a) (b)



(c)

Figure 6. Performance evaluation of the proposed converter: (a) Efficiency curve (b) Transient response and (c) Output harmonic distortion.

To increase the reliability of the proposed converter design in real world conditions, its performance was evaluated under varying environmental and operational conditions. The simulations deal with changes in solar irradiance levels in between 200 and1000 W/m². İn addition to different temperatures from 25 to 75 °C and input voltage variations also with a range of 10 to14 V. The efficiency showed an increasing with irradiance from 87.2% at 200 W/m² to 95.8% at 1000 W/m², which was lower than ideal techniques due to low conduction and switching losses when working at lower power levels. Output power effected only with about 8% to 12% when temperature increased. The ANN-based MPPT controller kept stable tracking performance but showed a mild drop in dynamic response during changing irradiance transitions. Output voltage regulation remained within small difference of about 5% of the required value under input changes, demonstrating acceptable stability. These results suggested the converter performed better under different operational conditions as shown in Fig. 7.

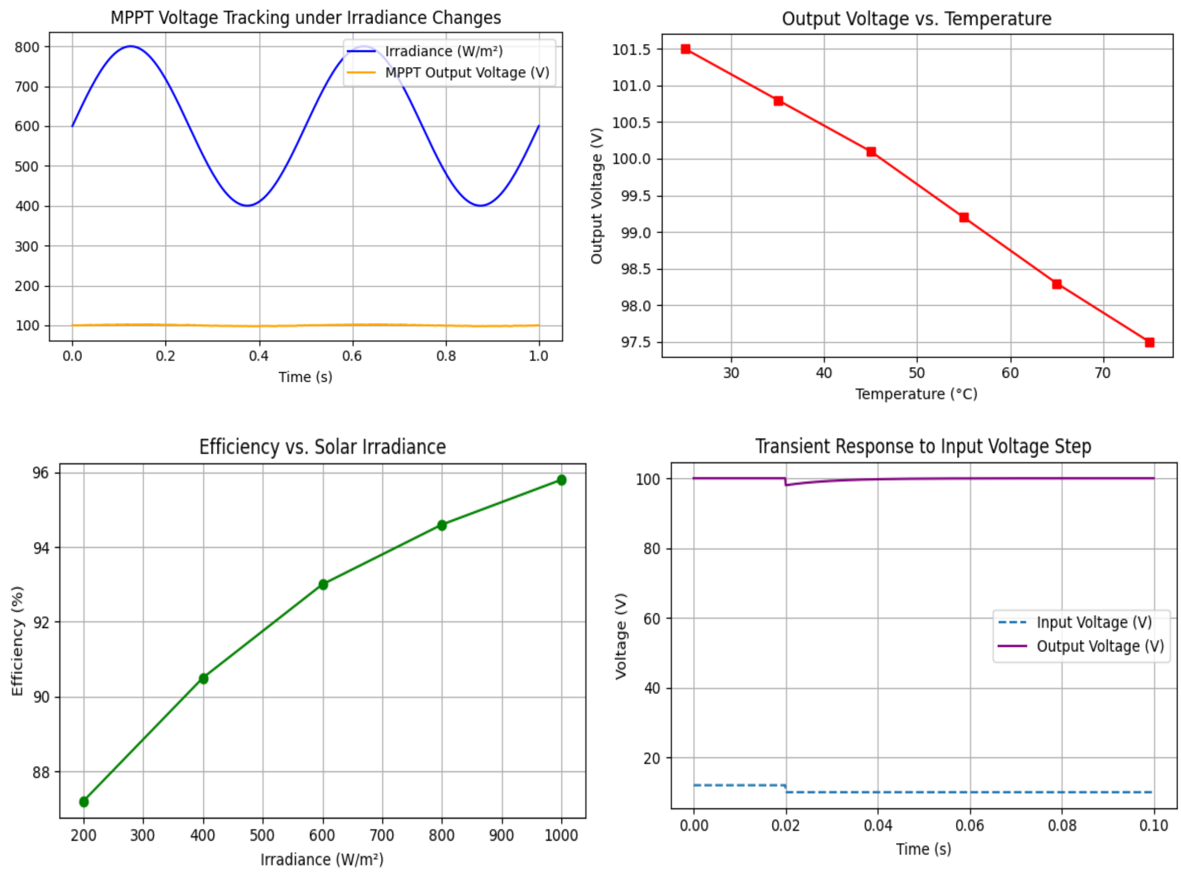


Figure 7. Performance evaluation under environmental and operational variations

Conclusion

The proposed DC-DC converter addressed critical challenges in power conversion for PV systems through its design with coupled-inductor and active-clamp architecture. The achievements were included with an 8.3 times the input voltage from 20 V to 100 V. The overall efficiency was 96.5% with a high reduction in switch voltage stress. The proposed design provided several advantages over existing works due to the ability to maintain high efficiency across different load conditions, while the total cost was minimized as well. This design also demonstrated significant improvements that including 15% lower losses at light loads compared to traditional designs. These advancements proved that the proposed converter could be applied to various applications, not only for PV but also for charging systems and power supplies. Future research should focus on using digital control methods for smart grid applications and using wide-band gap devices for efficiency increment. This work represented a contribution to power electronics by providing several key as high performance with cost minimization, that meet the growing demands of modern renewable energy applications. This work is relevant to industry applications where energy efficiency and power density are considered as the main required factors. As renewable energy systems continue to evolve, the proposed design architecture offered a stable solution that could be adapted to various voltage requirements. This research provided basic steps for future developments in sustainable energy infrastructure.

The comparative analysis in Table 3 highlighted the design points of different DC-DC converter topologies for PV system. The Proposed Model achieved a balanced profile despite its higher cost and medium weight, it delivered fast transient response and a compact design which making it favorable for high performance applications. These parameters confirmed the Proposed strength in real world PV design. Additional performance evaluation of the proposed converter under different conditions proven its suitability for PV systems. With an efficiency of 96.5% at full load and a fast transient response of around 1.8 ms, the converter proved effective in handling load changes with minimal voltage.

The ANN based MPPT controller kept a high tracking efficiency of 98.9% which ensuring optimal power extraction under changing irradiance and different temperature conditions. Moreover, the system showed thermal stability up to 65 °C and exhibited low THD with about 3.1% that meeting electromagnetic standards. Environmental testing revealed stable operation with only minor efficiency and output variations, confirming the converter's reliability across diverse scenarios. These results validated the proposed design capability for efficient, and robust operation in real-time PV applications.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

* This study was approved by the Ethics Committee of the College of Engineering, University of Diyala (approval date: 10/02/2025). The authors declare that the participants received sufficient information about the research and signed the consent forms.

Conflict of Interest

* The authors declare that they have no conflict of interest.

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