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# Enhancement of solar energy utilization through an artificial neural network controller featuring a dynamic learning rate in conjunction with an ultra-lift Luo converter

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## Abstract

With the growing need for sustainable energy solutions, optimizing photovoltaic (PV) systems becomes crucial. PV systems, while effective, are subject to efficiency fluctuations due to varying irradiance and temperature, posing significant challenges in maintaining optimal performance. This study explores the enhancement of PV systems by integrating an Ultra Lift Luo (ULL) converter with an Artificial Neural Network (ANN) controller using a dynamic learning rate. The ULL converter, known for its high voltage conversion gain, is suitable for various load requirements in PV systems. The ANN controller, equipped with a dynamic learning rate, adapts in real-time to changes in environmental conditions, ensuring superior performance compared to static learning rate methods. This dynamic approach allows the ANN to efficiently manage non-linear and variable inputs from the PV cells, optimizing the Maximum Power Point Tracking (MPPT) process. Our research involved simulating the PV system model using MATLAB/Simulink, incorporating the ULL converter and ANN controller using dynamic learning rate. The study compared the performance of the ANN controller with dynamic learning rate against a static learning rate approach, using 201 data samples for training. The dynamic learning rate not only enhances adaptability but also provides more stable voltage and power outputs under varying irradiance and temperature conditions. These results demonstrate the potential of dynamic learning rates in optimizing PV system performance, highlighting their role in advancing renewable energy technologies.

**Keywords:** Artificial neural network; Dc-dc Ultra lift luo converter; Dynamic learning rate; Maximum power point tracking; photovoltaic system; Static learning rate

## 1 Introduction

The shift towards renewable energy sources is imperative to mitigate the adverse effects of fossil fuel consumption. Fossil fuels, while historically pivotal for industrial growth, contribute significantly to environmental pollution and global warming. As global awareness of environmental issues increases, there is a growing emphasis on adopting sustainable and eco-friendly energy solutions. Renewable energy sources offer a viable alternative to traditional fossil fuels, providing a cleaner and more sustainable way to meet the world's energy demands [1].

Among the various renewable technologies, photovoltaic (PV) systems stand out for their direct conversion of sunlight into electricity. PV systems harness solar energy, one of the most abundant and inexhaustible resources available. This technology not only reduces dependence on fossil fuels but also minimizes greenhouse gas emissions, playing a crucial role in combating climate change. However, the efficiency of PV systems is influenced by environmental variables such as irradiance and temperature, which can fluctuate throughout the day and across seasons. These fluctuations pose

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significant challenges in maintaining optimal performance, often leading to suboptimal energy conversion and reduced efficiency [2].

To address these challenges, advanced power electronic devices such as DC-DC converters are employed. The Ultra Lift Luo (ULL) converter, in particular, has gained attention for its ability to boost and regulate voltage levels efficiently to meet varying load demands. The ULL converter is renowned for its high voltage conversion gain and its capacity to handle a wide range of input conditions, making it ideal for integration with PV systems. By efficiently managing the power output, ULL converters ensure that the energy generated by PV panels can be utilized effectively, thereby enhancing the overall efficiency of the system [3].

However, the effectiveness of the ULL converter is highly dependent on the control strategy employed. Traditional controllers, such as Proportional-Integral-Derivative (PID) controllers, often struggle with the dynamic and non-linear characteristics of PV inputs. These controllers can exhibit slow response times and may not adequately adapt to rapid changes in environmental conditions, resulting in suboptimal performance. This limitation necessitates the exploration of more advanced control techniques that can provide better adaptability and efficiency.

To overcome these limitations, this study introduces an Artificial Neural Network (ANN) controller equipped with a dynamic learning rate. The ANN controller is designed to enhance the system's ability to adapt to changing conditions by continuously adjusting the learning rate in real-time. Unlike static learning rate methods, a dynamic learning rate allows the ANN to respond more effectively to the non-linear and variable nature of PV inputs. By doing so, it ensures optimal performance and higher efficiency, even under fluctuating environmental conditions [4].

This research investigates the integration of the ANN controller with a ULL converter in a simulated PV system model using MATLAB/Simulink. The study aims to compare the performance of the ANN controller with a dynamic learning rate against traditional static learning rate approaches. The findings reveal significant improvements in energy conversion efficiency, with the dynamic learning rate achieving an efficiency of 96.9314%, compared to 92.9241% with the static learning rate. The dynamic learning rate not only enhances adaptability but also provides more stable voltage and power outputs under varying irradiance and temperature conditions. These results underscore the importance of advanced control strategies in advancing renewable energy technologies and optimizing the efficiency of PV systems.

The potential of dynamic learning rates in optimizing PV system performance highlights their role in the future of renewable energy. As the demand for sustainable energy solutions continues to rise, integrating advanced control techniques such as the ANN with dynamic learning rates will be crucial in maximizing the efficiency and reliability of PV systems. This study contributes to the growing body of research focused on enhancing renewable energy technologies, demonstrating that innovative approaches can lead to significant improvements in performance and sustainability [5].

## 2 Material and methods

### 2.1 PV System Model

This section provides a detailed description of the PV system model, highlighting its components and the integration of the ANN controller. The PV array model inputs solar Irradiance (G) and Temperature (T) and outputs Voltage (V) and Power (P) for the ANN controller. The system incorporates a DC-DC Ultra Lift Luo Converter, which plays a pivotal role in adjusting the operating point to maximize power output. The reference voltage ($V_{pv}$) is dynamically generated based on ANN algorithm predictions, which utilize a dynamic learning rate. This dynamic learning rate allows the ANN controller to adapt in real-time to changing environmental conditions, ensuring optimal performance and efficient real-time optimization of the PV system [6].

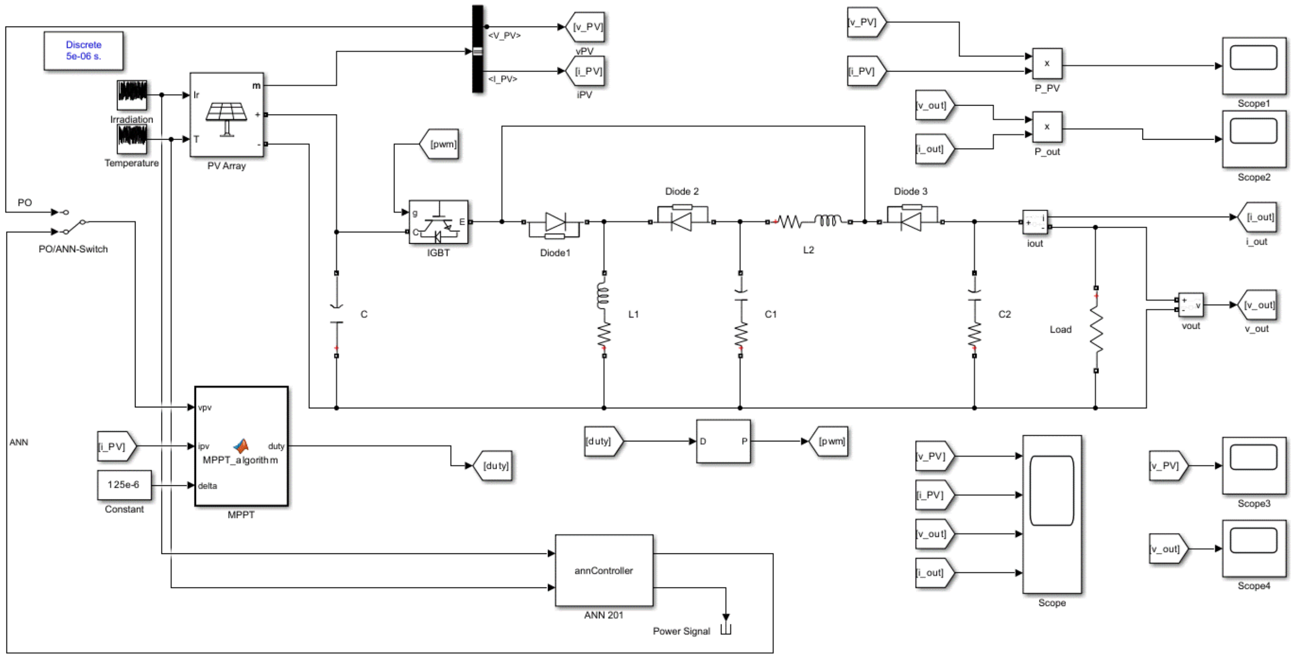

**Figure 1** MATLAB/Simulink diagram for The Proposed PV system

### 2.2 Mathematical Solar Array Modeling

Mathematical solar array modeling is essential for understanding and predicting the behavior of photovoltaic (PV) systems under varying environmental conditions. The primary objective of such modeling is to accurately represent the electrical characteristics of the solar array, which typically consists of multiple solar cells connected in series and/or parallel configurations. The fundamental equation governing the output current (I) of a solar cell is derived from the Shockley diode equation, modified to include the effects of solar irradiance and temperature. This equation considers the photo-generated current ($I_{ph}$), the diode saturation current ($I_D$), the series resistance ($R_s$), the shunt resistance ($R_{sh}$), and the current through the shunt resistance ($I_{sh}$), among other parameters. As seen in Figure 2, the resulting I-V characteristic curve at constant Temperature T = 25°C provides a detailed depiction of the cell's performance, which is crucial for optimizing the operation of the entire PV system [7].

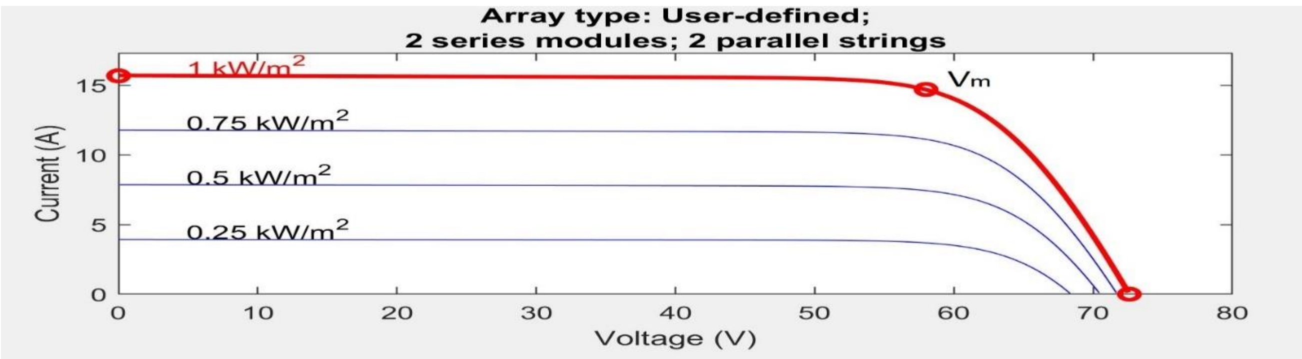


**Figure 2** Voltage Current (V-I) Characteristics Curve Under Different Levels of Sunlight Intensity

$$I = I_{ph} - I_D - I_{sh} \quad (1)$$

Where:

- I is the output current of the PV cell.
- $I_{ph}$ is the photo-generated current.
- $I_D$ is the current through the diode.
- $I_{sh}$ is the shunt leakage current.

This study focuses on the detailed modeling of a 213.15-Watt photovoltaic (PV) array, emphasizing its construction using p-n semiconductor junctions and its sensitivity to variations in solar irradiance and temperature. The voltage and power outputs are crucial metrics for assessing the PV array's operational efficiency, which is essential for its deployment in renewable energy systems. Accurate modeling enables artificial intelligence AI-based predictions and enhancements of the PV array's performance across a wide range of environmental conditions.

### 2.3 Modeling and Simulation of 213.15W PV array

The 213.15-Watt photovoltaic (PV) array utilized in the designed PV system was meticulously chosen from the MATLAB/Simulink toolbox for simulation purposes. This selection ensures access to comprehensive information regarding the array's electrical properties and includes visual aids that illustrate its performance under varying temperature and irradiance conditions. Figure 3 provides a graphical representation of the selected PV array model from MATLAB/Simulink, showcasing its dynamic response to different environmental factors. Additionally, Table 1 presents detailed electrical parameters that define the PV array, offering a thorough understanding of its capabilities and performance metrics across a range of operational scenarios. These parameters are crucial for predicting the array's behavior and optimizing its integration into renewable energy systems. By leveraging MATLAB/Simulink's advanced simulation tools, the study ensures precise modeling and analysis, facilitating the development of efficient and robust PV systems [8].

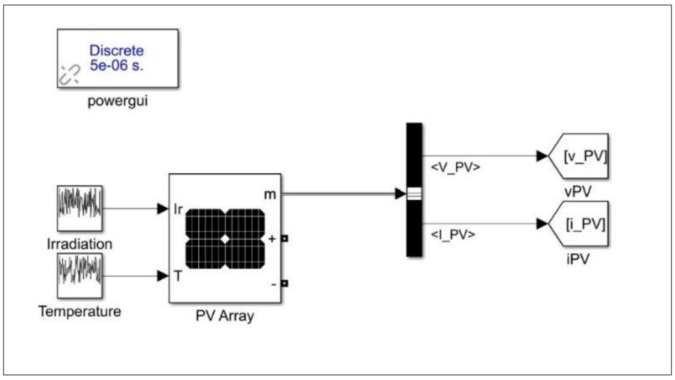


**Figure 3** MATLAB/Simulink diagram for the proposed designed PV array model

**Table 1** Electrical Characteristics of The PV Module

| **Description** | **User-defined** |
|---|---|
| Maximum power | 312.15 W |
| Voltage at Pmax (Vmax) | 29.00 V |
| Current at Pmax ($I_m$) | 7.35 A |
| Short Circuit current ($I_{sc}$) | 7.84 A |
| Open circuit voltage | 36.30 V |
| Temperature coefficient Ki | 0.102 A/°C |

The Voltage-Current (V-I) characteristics curve illustrates the relationship between the voltage and current output of the PV array under specific conditions, as depicted in Figure 4. This curve is crucial for understanding the performance of the PV array at different temperatures, specifically at 25 °C and 45 °C. The curve reveals that the current output remains relatively stable as the voltage increases, until it nears a critical threshold close to the open-circuit voltage. Beyond this threshold, the current output drops sharply. This behavior is essential for optimizing the PV array's performance and ensuring it operates efficiently under various environmental conditions [9].

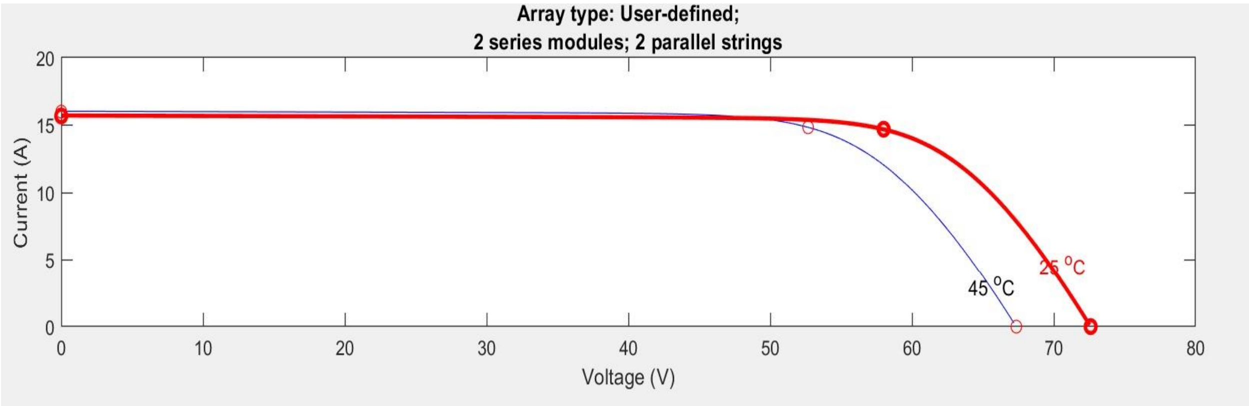


**Figure 4** Voltage-current (V-I) characteristics curve at a temperature of 25 °C and 45 °C

## 2.4 Advanced DC - DC Ultra Lift Luo Converter Model

### *2.4.1 Overview of the Ultra Lift Luo Converter*

The DC-DC Ultra Lift Luo (ULL) converter is an advanced component designed to effectively convert and regulate voltage levels within photovoltaic (PV) systems. It is optimized to boost the typically low and variable output voltage from PV arrays to a more usable and stable level, making it highly suitable for practical applications [10].

### *2.4.2 Techniques for Voltage Elevation*

- Incremental Voltage Boost (Arithmetic Progression): Traditional voltage boosting designs use an arithmetic sequence to incrementally raise the output voltage. This method provides a gradual and predictable increase in voltage, which is beneficial for basic voltage conversion and regulation tasks.
- Enhanced Voltage Boost (Geometric Progression): The Ultra Lift Luo converter leverages geometric progression to achieve a more substantial and efficient voltage increase. This technique significantly enhances the voltage amplification process, resulting in improved performance and efficiency.

### *2.4.3 Component Configuration and Circuit Design*

The ULL converter utilizes a strategic arrangement of inductors, capacitors, diodes, and an Insulated Gate Bipolar Transistor (IGBT) switch to achieve precise voltage transformation. This configuration ensures efficient energy conversion, maintaining stability and reliability throughout the process, which is essential for achieving the desired voltage output.

The operation of the converter is based on switching mechanisms that control how energy is stored and released within the inductors and capacitors. This controlled energy management results in a gradual increase in output voltage, following an incremental pattern similar to arithmetic progression.

### *2.4.4 Benefits Compared to Conventional Converters*

- **Superior Voltage Gain:** Unlike traditional converters such as Boost, Cuk, and SEPIC, which have limited voltage increase capabilities, the Ultra Lift Luo converter excels in achieving significantly higher voltage levels. By employing geometric progression, it enhances efficiency and performance in voltage transformation applications.
- **Harmonic Reduction:** Excessive harmonics can disrupt operations and reduce system efficiency. The Ultra Lift Luo converter effectively minimizes harmonic distortion, resulting in a cleaner and more efficient power output, thereby enhancing overall system performance.
- **Optimized Power Factor:** Conventional converters often suffer from poor power factor, leading to inefficiencies. The Ultra Lift Luo converter is specifically engineered to optimize and maintain a favorable power factor, ensuring efficient operation and reducing energy losses, which improves overall system reliability.
- **Enhanced Efficiency:** The converter's design reduces current ripples, decreasing energy losses and enhancing overall system efficiency. By ensuring smoother and more stable current flow, it minimizes heat generation and switching losses, optimizing energy usage [31]. This not only conserves energy but also extends the reliability and longevity of connected equipment. Reduced current ripples also help maintain high power quality, ensuring consistent and reliable operation of electrical systems.

- **Extended Voltage Range:** The converter's ability to achieve a wider voltage range makes it ideal for applications that require significant voltage increases, such as integrating photovoltaic systems with external loads.

#### *2.4.5 Application in Photovoltaic Systems*

- **Handling Unregulated PV Output:** PV systems typically produce an unregulated output voltage that varies with changes in solar irradiance and temperature. This unregulated output is often inadequate for directly powering loads or integrating with the grid.
- **Voltage Stabilization:** The Ultra Lift Luo converter is essential for elevating and stabilizing the voltage output of PV systems. This controlled voltage enhancement ensures consistency and reliability, making the power output suitable for various electronic devices and systems. By maintaining a steady output, the converter enables efficient use of solar-generated electricity, enhancing overall system performance and reliability.

#### *2.4.6 Integration with External Loads*

The Ultra Lift Luo converter optimizes the PV system's capability to deliver consistent and reliable power to external loads. This converter ensures that the voltage output meets specified standards, thereby improving the overall dependability and operational effectiveness of the PV system.

The Ultra Lift Luo converter is constructed with the following key components:

- Switch: The IGBT acts as a semiconductor switch that is crucial for regulating the converter's duty cycle and operational efficiency.
- Diodes: Standard diodes (D1, D2, and D3) are essential for directing current flow in one direction while blocking reverse current to maintain proper operation and prevent undesired electrical feedback.
- Energy Storage Components: Inductors (L1 and L2) store energy in the form of a magnetic field, ensuring consistent current flow and enhancing system stability. Capacitors (C1 and C2) smooth out voltage fluctuations, ensuring a consistent power supply. Both capacitors are designed with identical values, contributing equally to the circuit's stability and efficiency.

The converter employs the ultra-lift technique to consistently raise the output voltage above the input voltage of the PV array. This method incrementally increases the voltage in a geometric progression, ensuring that the output remains positively offset from the input. This design guarantees efficient power transformation, essential for maximizing the converter's performance in various applications. It ensures reliable operation by maintaining a stable output voltage, thereby optimizing the overall efficiency and functionality of the system.

The functional principles and dynamic response of the Ultra Lift Luo converter are governed by the equations presented below. These equations elucidate its operational mechanisms and how it interacts with varying input parameters:

The Transfer Gain (K) denotes the ratio of the output voltage ($V_o$) to the input voltage ($V_{in}$), illustrating the extent to which the converter amplifies the input voltage to achieve the desired output voltage:

$$K = \frac{V_o}{V_{in}} \quad \ldots\ldots (2)$$

This equation is fundamental in understanding the voltage amplification characteristics of the ULL converter.

The connection between the input voltage ($V_{in}$), output voltage ($V_o$), and transfer gain (K) for the Ultra Lift Luo converter is governed by a specific mathematical equation. This equation illustrates how variations in Vin influence Vo, scaled by the factor K. It is essential for understanding how the converter amplifies the input voltage to produce the desired output voltage, which is crucial for determining its operational characteristics and efficiency in various applications [11]:

$$K = \frac{V_O}{V_{in}} = \frac{D(2-D)}{(1-D)^2} \quad \ldots\ldots (3)$$

This formula provides a quantitative understanding of the voltage amplification process, ensuring accurate predictions of the converter's behavior under different operating conditions.

The DC-DC Ultra Lift Luo converter is an advanced and efficient device tailored to boost voltage levels. It utilizes components such as an Insulated Gate Bipolar Transistor (IGBT), diodes, inductors, and capacitors to achieve significant voltage amplification, ensuring output stability with minimal ripples and disturbances. The converter's design principles are encapsulated in its operational equations, which are vital for engineers to design, optimize, and evaluate its performance in various applications, particularly in photovoltaic (PV) systems. These equations shed light on the converter's voltage transformation capabilities, ensuring dependable and efficient power conversion from solar energy sources to meet diverse electrical requirements. The functional dynamics of the Ultra Lift Luo converter are further clarified through its block diagram, depicted in Figure 5, which outlines the core components and the flow of electrical energy within the system. This schematic representation is crucial for comprehending the converter's architecture and the interactions between its IGBT, diodes, inductors, and capacitors. Understanding these interactions is key to appreciating how the converter effectively boosts voltage without inversion, making it essential for various electronic and energy system applications.

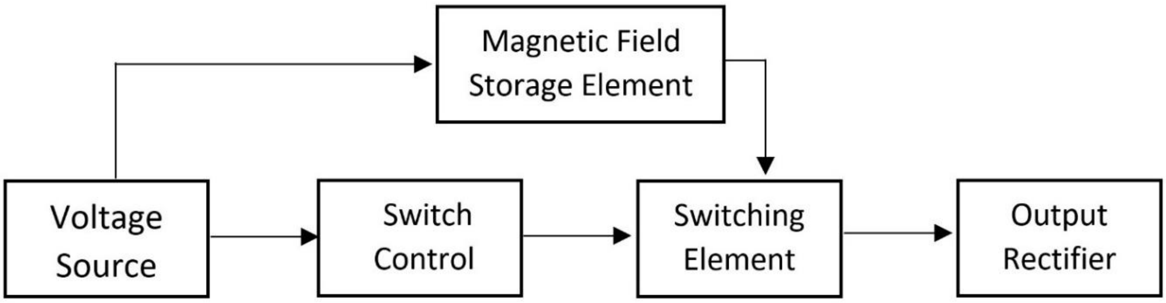


**Figure 5** The Designed Block Diagram of a DC-DC Ultra Lift Luo Converter

Using a DC source with an input voltage ($V_{pv}$) of 10V and a designated duty cycle (D) of 0.6 for the DC-DC Ultra Lift Luo converter, we can calculate the expected output voltage ($V_o$) to be 52V. This calculation is based on the converter's operational parameters, which define the relationship between the input voltage, duty cycle, and resulting output voltage. These parameters are crucial for understanding the converter's functionality and efficiency as specified in its design principles.

The transfer gain (K) and the associated equations provide a clear understanding of how the input voltage is converted to the output voltage. These equations are instrumental in elucidating the conversion mechanism, allowing for a comprehensive grasp of the voltage transformation process within the system. By applying these mathematical relationships, one can accurately predict and analyze the converter's performance, ensuring effective voltage regulation and optimization in various applications.

$$K = V_o / V_{in} = D(2-D) / (1-D)^2$$

$$K = 0.6(2-0.6) / (1-0.6)2 = 5.25$$

$$K = 5.25.$$

Now, set up the equation:

$$K = V_o / V_{in}$$

Cross-multiply to solve for $V_o$:

$$5.25 \times 10 = V_o$$

$$V_o = 52.5V$$

Verify the Gain (K)

Now substitute $V_o$ back into the gain formula to verify:

$$K = 52.5 / 10$$

$$K = 5.25$$

The calculated gain K matches our initial calculation, confirming that K = 5.25.

This computation validates the recorded output voltage of 52.5V when supplied with a 10V input and operated at a 60% duty cycle, affirming the accuracy of the simulation's outcomes.

Figure 6 depicts the experimental setup and simulation outcomes using a block diagram. The results confirm that by employing a 60% duty cycle, the converter effectively increases the input voltage of 10V from the DC source to 52.5V as demonstrated in the Ultra Lift Luo converter's output.

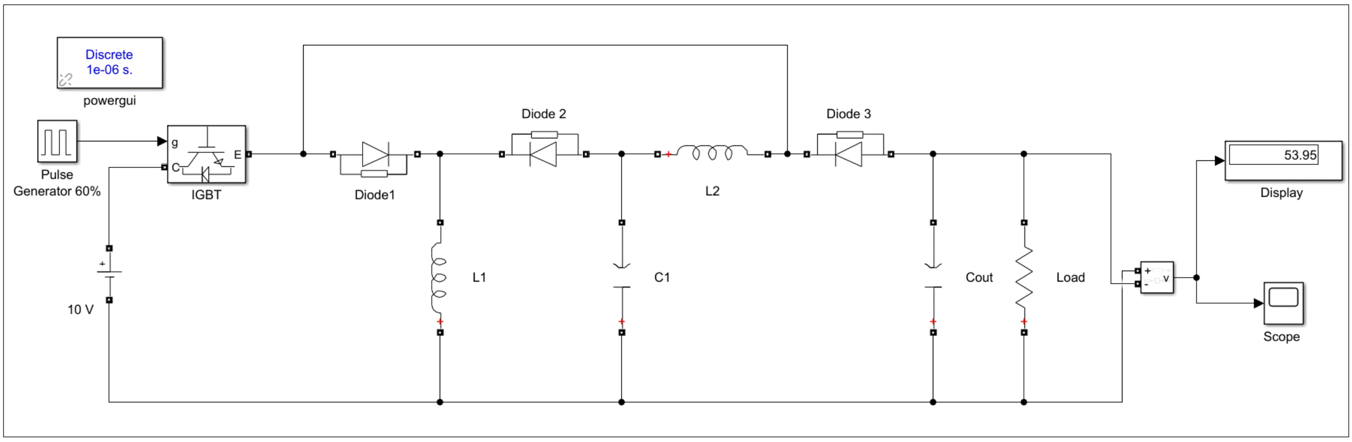


**Figure 6** MATLAB/Simulink at 60% Duty Pulse Generator

The analysis and evaluation, incorporating both calculations and block diagrams, align seamlessly with the simulation outcomes, affirming the effectiveness of the Ultra Lift Luo converter in boosting voltage from a DC source. This converter demonstrates exceptional efficiency in elevating input voltage to a stable and higher output voltage, making it highly suitable for diverse applications. Figure 7 highlights the converter's capability, showing a rapid and consistent rise in output voltage, which outperforms traditional converters such as Cuk or Boost that often suffer from overshooting and prolonged stabilization periods. Both theoretical calculations and simulations underscore the converter's robustness, making it an ideal choice for integrating photovoltaic systems with external loads requiring stable, regulated higher voltages. This ensures a reliable power supply, essential for applications demanding consistent energy delivery without fluctuations, thereby significantly enhancing the reliability and efficiency of renewable energy systems in practical scenarios.

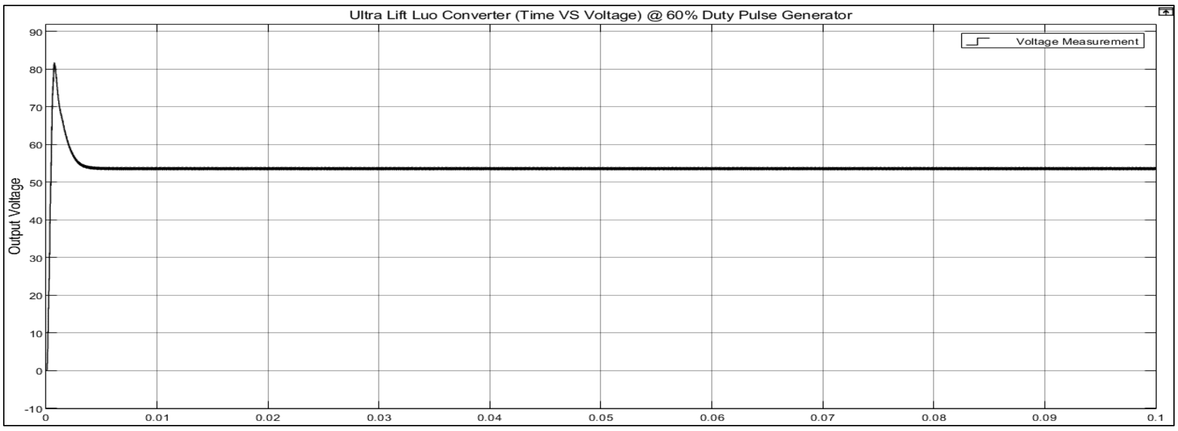


**Figure 7** Ultra Lift Luo Converter Time VS Voltage at 60% Duty Pulse Generator

### 2.5 Artificial Neural Network (ANN)

Artificial Intelligence (AI) controllers are increasingly being adopted to enhance the performance and efficiency of photovoltaic (PV) systems. Among various AI techniques, the integration of Artificial Neural Networks (ANNs) has shown significant promise in optimizing the Maximum Power Point (MPP) tracking of PV arrays [12]. This AI-driven method improves overall system performance by dynamically adjusting to changing environmental conditions, thereby maximizing the energy output from solar panels. The use of ANNs for MPP tracking allows for real-time adaptability, which is crucial for maintaining high efficiency in fluctuating weather conditions. Advanced simulation tools like MATLAB/Simulink facilitate the development and validation of these AI controllers, providing a reliable foundation for their practical implementation.

#### *2.5.1 Comparative Analysis with Dynamic Learning Rate*

In our study, we focused on enhancing the ANN controller's training by using a dataset comprising 201 samples. We compared the efficiency of the ANN with a static learning rate to that of an ANN with a dynamic learning rate [13] [14]. The results indicated that the ANN with a dynamic learning rate significantly outperformed the static learning rate approach. The dynamic learning rate allowed the ANN to adapt more effectively to changing environmental conditions, ensuring consistent MPP tracking, optimized power output, and maintained efficiency. These findings were validated through simulations conducted using MATLAB/Simulink, which confirmed the enhanced performance and reliability of the dynamically trained ANN controller. This advancement highlights the superior adaptability and efficiency of the dynamic learning rate, making it a crucial enhancement for modern PV systems aiming to achieve optimal performance in renewable energy generation.

In our previous research, we utilized a static learning rate for the Artificial Neural Network (ANN) controller integrated with the Ultra Lift Luo converter in PV systems. This approach provided notable improvements in voltage regulation and efficiency. However, static learning rates can limit the ANN's ability to adapt to rapid changes in environmental conditions, such as fluctuating solar irradiance and temperature.

In this study, we introduce a dynamic learning rate for the ANN controller, which allows real-time adjustments to the learning rate based on the current operating conditions. This dynamic approach enhances the system's ability to quickly and efficiently respond to environmental variations, optimizing the Maximum Power Point Tracking (MPPT) process and overall system performance.

The enhanced ANN controller with a dynamic learning rate is simulated using MATLAB/Simulink, incorporating the Ultra Lift Luo converter. The simulations reveal that the dynamic learning rate significantly improves the system's adaptability and efficiency compared to the static learning rate approach. The new method not only achieves higher voltage regulation but also ensures more stable power outputs, which is crucial for reliable energy delivery in practical applications [15].

By comparing both approaches, it is evident that the dynamic learning rate provides a superior solution for integrating PV systems with external loads, ensuring consistent and efficient energy conversion. This advancement highlights the importance of adaptive control strategies in enhancing the performance and reliability of renewable energy systems, paving the way for more resilient and efficient PV applications.

## 3 Results and Discussion

### 3.1 Artificial Neural Network (ANN) Static VS Dynamic Learning Rate

In Table 2, the efficiency comparison of the ANN controller using 201 samples with both static and dynamic learning rates is presented. When employing a static learning rate, the ANN controller achieved an efficiency of 92.9241%. However, introducing a dynamic learning rate significantly enhanced the performance, demonstrating a notable increase in efficiency.

The results underscore the critical role of dynamic learning rates in optimizing the performance of ANN controllers. By allowing the learning rate to adapt in real-time, the ANN can more effectively respond to varying environmental conditions, thereby improving the Maximum Power Point (MPP) tracking process. This adaptability results in a more efficient power output and overall enhanced system performance compared to the static learning rate approach.

**Table 2** Comparison of ANN Controllers with Static and Dynamic Learning Rates (201 Samples)

| No. | Controller Type | Efficiency |
|---|---|---|
| 1 | ANN with 201 Samples (Static Learning Rate) [16] | 92.9241% |
| 2 | ANN with 201 Samples (Dynamic Learning Rate) | 96.6317% |

## 4 Conclusion

This study demonstrates the significant benefits of integrating an Artificial Neural Network (ANN) controller with a dynamic learning rate into a photovoltaic (PV) system utilizing an Ultra Lift Luo (ULL) converter. The findings reveal that the ANN controller with a dynamic learning rate substantially enhances the Maximum Power Point Tracking (MPPT) process, improving system efficiency to 96.6317%, compared to 92.9241% with a static learning rate. The dynamic learning rate allows the ANN controller to adapt in real-time to varying environmental conditions, such as changes in solar irradiance and temperature, ensuring optimal performance and efficient energy conversion. This adaptability is crucial for maintaining consistent power output and high system reliability, essential for practical renewable energy applications. The research underscores the importance of advanced AI-based control strategies in optimizing PV system performance. By leveraging the dynamic learning rate, the ANN controller effectively manages non-linear and variable inputs from the PV array, ensuring maximum energy yield and enhancing overall system efficiency. The integration of dynamic learning rates in ANN controllers presents a promising approach for advancing renewable energy technologies. This study contributes to the growing body of research focused on enhancing the performance and sustainability of PV systems. Future research should explore further optimization techniques and real-world implementations to continue improving the efficiency and reliability of renewable energy systems. The findings highlight the potential impact of using AI controllers with dynamic learning rates to achieve significant advancements in renewable energy, paving the way for more resilient and efficient PV applications.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The authors declare that no conflicts of interest exist between them.

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