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Machine learning based cascaded ANN MPPT controller for erratic PV shading circumstances

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ABSTRACT

Power generation is challenged to meet energy demand during peak hours. As a result of limited non-renewable energy resources, power utilities heavily rely on fossil fuels. Therefore, scientists and researchers are looking for some distributed generators to provide additional power during peak hours. During such period, load demand is solved using solar power. As a consequence, grid-connected solar photovoltaic (PV) systems are catching the attention owing to their ability to significantly reduce the use of fossil fuels. Under partial shading condition (PSC), this paper utilizes Luo converter along with cascaded artificial neural network (ANN), which is a machine learning based maximum power point tracking (ML-MPPT) approach for tracking optimal power from PV system. The gained DC supply is converted into AC voltage using 1 Φ VSI attached to the system. In addition, PI controller engaged controls the voltage at grid side and results in effective grid synchronization. Furthermore, MATLAB/Simulink analysis is carried out and the outcomes reveal the effectiveness of proposed system with 98% efficiency under different PV circumstances.

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1. INTRODUCTION

Renewable energy sources (RES), contrary to fossil fuels, are abundant and do not pollute the environment with CO_2 emissions, as a result, they are becoming a more important power source around the world [1]. Cumulatively, renewable energy production capacity is expected to reach 3064 GW by 2021 [2]. As a RES, PV are among the most important [3]. Several nations are making significant investments in the fields of RES at utility and distributed scale. Due to favorable government regulations and the recent developments in power electronics, cost of producing PV energy has decreased by 90% over past ten years [4]. While PV systems have benefits such being a natural, clean energy source it is capable of generating electricity anywhere there is warm weather, they also have certain drawbacks. Changes in environmental factors affects maximum power point (MPP), PV output voltage and current [5]–[7] which needs a controller to overcome these challenges.

Many different approaches are suggested to get the most power and efficiency out of PV panel, and each has its own benefits and drawbacks. Therefore, for each system, the best approach needs to be selected. The perturb and observe (P&O) based maximum power point tracking (MPPT) charge controller is evaluated [8] and the performance of different P&O algorithms are examined [9]. An incremental conductance (IncCond) [10], [11] approach is used to track MPP while avoiding the challenges of P&O method. The intricacy of IC technique is its main disadvantage. The P&O and hill climbing [12], [13] technique are implemented to track MPP. The performance of sliding mode controller (SMC) and model reference adaptive control (MRAC) MPPT algorithms are compared [14] based on its tracking speed, efficiency. The traditional methods perform poorly because oscillations are more pronounced around MPP during tracking [15]. Most authors have engrossed on soft computing or biological MPPT strategies to address the problems with traditional MPPT methods. Evolutionary algorithms which include neural networks (NN), fuzzy logic controllers (FLC), and artificial neuro fuzzy interface systems (ANFIS) [16]–[18] results in better tracking of MPP. The steady state oscillations at MPP under dynamic irradiation settings are reduced using ANN technique [19]. A novel fuzzy logic–IncCond based MPPT controller is implemented to reduce the step size and convergence time [20]. However, ANN requires more data with multiple layers. Similarly, FLC technique has limitations and cannot be changed after rules are established. Hence, the proposed work adopts cascaded ANN technique, an ML based approach for tracking of optimal PV power.

Grid performance is greatly influenced by the DC-DC converter used. In solar PV systems, abnormally high exposure to sunlight is the main constraint. A variety of DC-DC converters are used to address this issue and provide a stable output voltage for use in applications [21]. Boost, buck-boost, CUK and Single Ended Primary Inductance converters (SEPIC) are some of the converters utilized in enhancing voltage. In the way, DC voltage is increased using boost converter [22], which lacks overcurrent protection. The PV output voltage is stabilized using a CUK converter [23] to get around this problem. The CUK converter's disadvantage is its high operational complexity. High magnetic inrush current and the absence of load-side current protection from short circuit failures are problems with SEPIC [24]. A P&O based MPPT charge controller is evaluated using ZETA converter for battery charging, which shows poor performance during partial shading conditions (PSC) [25]. As a result, the majority of conventional boost converters cannot achieve constant output voltage, minimal current ripples, or a wide range of input and output tasks. Hence, the proposed work introduces Luo converter as it has the ability to function in both buck and boost modes, with a range of input voltage levels.

In the proposed work, the generated DC power is supplied to Luo converter. The proposed ML based cascaded ANN controller predicts the ideal voltage and duty cycle needed for operating PV panels at their MPP by continually monitoring voltage and current of PV panels. The assessed optimal voltage is utilized as input to Luo converter, thereby adjusting the duty cycle to control output voltage. Finally, the AC power from 1Φ VSI is transferred to grid and results in grid synchronization.

2. PROPOSED SYSTEM

Since the last decade, inverter powered PV grid configurations are widely employed to supply power needs and integrate renewable energy sources into power networks. Accordingly, a ML based MPPT strategy is established in this paper for effective grid stability under normal and partial shading condition (PSC). The proposed work employs an array of solar PV panels that generates DC power and supplies to the Luo converter. Since, the power generated by PV varies due to irradiance and temperature optimal tracking of PV power is essential. Hence, an ML based cascaded ANN controller is engaged for MPP tracking in this research work. The block diagram of the proposed system is shown in Figure 1.

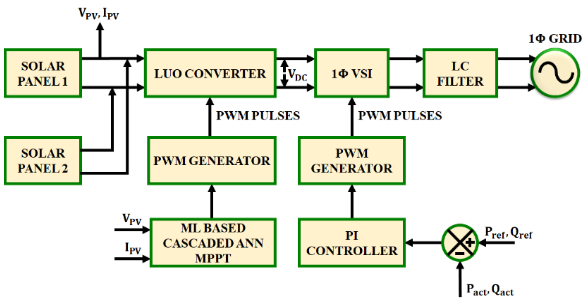


Figure 1. Proposed ML based MPPT architecture for grid-tied system

The main reason for choosing a cascaded ANN MPPT controller is its superior accuracy in tracking the MPP of PV system. It offers adaptability to varying environmental conditions and exhibits robustness, resulting in improved energy extraction and system performance. The adoption of cascaded ANN controller continuously monitors and evaluates the power under normal as well as PSC. This MPPT controller modifies the duty cycle of Luo converter to control output voltage and make sure the system is operating as efficiently as possible. The DC power obtained from Luo converter is fed to grid through grid-tied inverter, and guarantee the power generated by PV system is in synchronization with grid. The following section entails the description of system components.

2.1. PV system modelling

A PV cell is a semiconductor device that uses photovoltaic effect to transform light into electrical energy. Several PV cells are connected in parallel and series to form a PV array. While the current in array is increased by a parallel connection, the voltage is increased by series connections. The two major parameters which will give huge impact on solar power generation are solar irradiance level and temperature which are purely depends upon environmental conditions. The output power of PV cells are considered stable when ecological conditions such as irradiance and temperature do not vary. In partial shading, there is a reduction in amount of sun radiation hitting a PV array. This results in a decrease in power output of the array, causing a variation in PV's characteristic performance. However, deployment of converter is essential for improving the voltage generated by PV, which is discussed as follows.

2.2. Operation of LUO converter

DC-DC Luo converters are employed in between PV arrays and inverters. Figure 2 depicts a typical circuit diagram for the Luo converter. From figure S represents power switch, $C_1 \ and \ C_2$ are capacitors, resistive load is denoted as R and D is the freewheeling diode. Inductors $L_1 \ and \ L_2$ serve as passive energy storage components. In order to analyze the operation of Luo converter, it is divided into two modes.

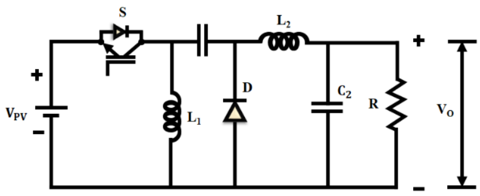


Figure 2. Equivalent configuration of Luo converter

2.2.1. Operation mode 1

In Figure 3(a), the depicted configuration represents the analogous setup of a Luo converter operating in mode 1. While switch ‘S’ is in ON mode, the supply voltage E charges the inductor L_1 and turns it on to regulate and adjust the output voltage. Both capacitor C_1 and inductor L_2 simultaneously absorb energy from the source. The capacitor C_2 supplies power to load.

2.2.2. Operation mode 2

As illustrated in 3(b), current drawn from source is zero when the switch is in OFF position. To charge capacitor C_1, current iL_1 passes via freewheeling diode. In order to maintain continuous operation, current iL_2 passes through the $C_2 - R$ circuit and freewheeling diode D. This allows for efficient voltage conversion, making it suitable for various applications where voltage step-up or step-down is required.
The expression for inductor current iL_2 on analysis is given by (1).

$$iL_2 = \frac{1-a}{a} iL_1 \tag{1}$$

The expression for duty cycle is given by (2).

$$a = \frac{T_{on}}{T} \tag{2}$$

The voltage output is denoted as (3).

$$V_0 = \frac{a}{1-a} V_{in} \tag{3}$$

Capacitor C_1 average voltage is expressed as (4).

$$V_{C_1} = \frac{a}{1-a} V_{in} \tag{4}$$

The expression for inductor L_1 and L_2 can be written as (5).

$$L_1 = \frac{aTV_{in}}{\nabla iL_1}, L_2 = \frac{aTV_{in}}{\nabla iL_2} \quad (5)$$

During OFF period, series capacitor charge C_1 increases by $iL_2 = i_0$ and it decreases by iL_1 during switched ON period. The charge on capacitor C_1 must not be altered by peak-to-peak voltage ripples across C_1. On evaluating in (5), the expression for C_1 becomes:

$$C_1 = \frac{1-a}{\nabla VC_1} Ti_1 \quad (6)$$

On a PV module's P-V curve, under uniform irradiance conditions, there is often only one extreme power point where PV module produces its greatest yield power. In order to achieve this highest productivity, MPPT techniques are used.

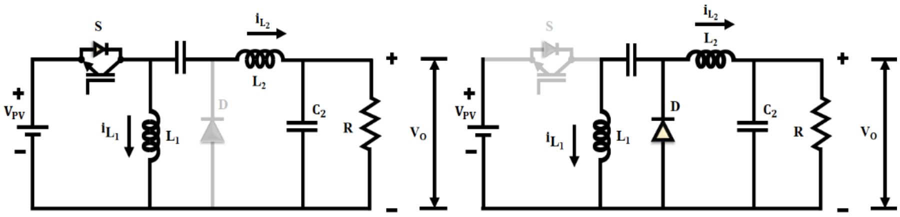


Figure 3. Operation of Luo converter: (a) mode 1 and (b) mode 2

3. ML BASED CASCADED ANN MPPT TECHNIQUE

The MPPT transmits appropriate control signals, to the converter based on output voltage and current of PV, by processing these data. Here, data is processed using reference values, errors are detected, and the Luo converter is controlled by an appropriate PWM signal using a duty cycle modification to maximize power. In this research, ML-based cascaded ANN as seen in Figure 4, uses ANNs to read current and voltage signals and determine voltage at which optimal power is generated. Thus, the reference voltage is determined. The array's current and voltage outputs serve as ANN1's inputs. The first neural network, ANN1, is capable of predicting the temperature and irradiance, which will be used as inputs by ANN2, the following NN. The second NN is trained to predict voltage at MPP. The controller of Luo converter serves as a point of reference. Utilizing a PWM and PI controller, the voltage error—the discrepancy between reference voltage and actual voltage is utilized to adjust duty cycle. Even under shifting irradiance and temperature circumstances, the ideal power point of PV module is tracked more precisely with the aid of a cascaded ANN MPPT controller. The controller is capable of learning from previous data and adapt to changing circumstances over time, which increases its efficiency in extracting most power out of PV module.

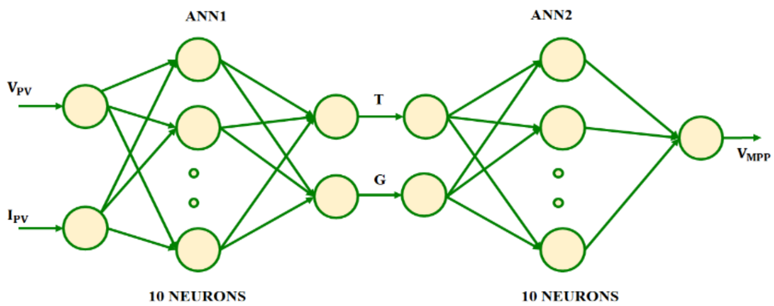


Figure 4. Structure of cascaded ANN

4. RESULTS AND DISCUSSION

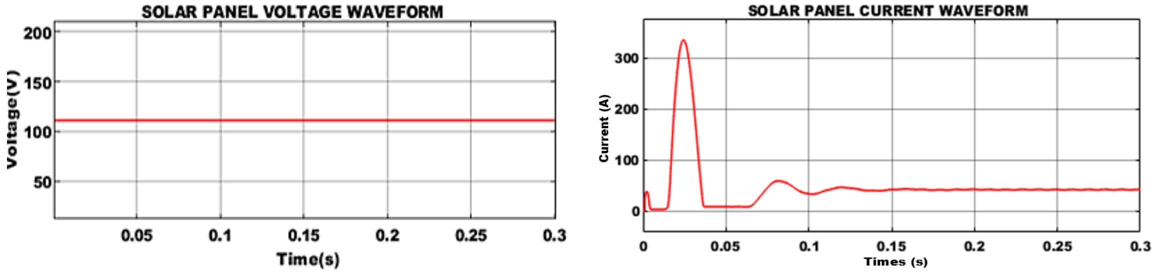
The proposed grid connected system with the adoption of Luo converter along with ML based cascaded ANN controller for tracking of MPPT is examined using MATLAB software to examine the efficacy of proposed grid tied system. The Table 1 lists the parameter specification utilized in this work, followed by MATLAB outcomes.

Table 1. Parameter specifications

	Parameter	Specification
Solar PV	Absolute temperature	25 °C
	Number of panels	15
	Open circuit voltage	22.6 V
	Short circuit current	41.6 A
	Short circuit voltage	12 V
Luo converter	Inductor L_1, L_2	13.46 mH
	Switching frequency	10 KHZ
	Capacitor C_1, C_2	0.347 μF
	Resistive load R	200 Ω

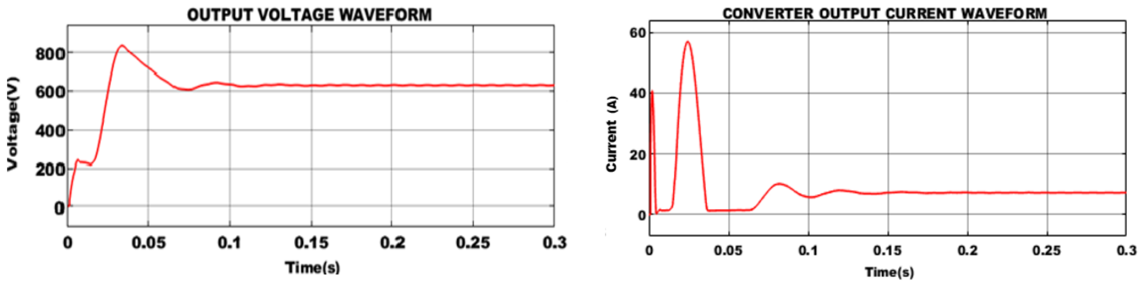
4.1. Case 1: Under normal condition

The input PV panel voltage and current under normal condition is illustrated in Figures 5(a) and 5(b). It is observed that 110 V with 58 A DC supply is nourished as input to Luo converter, for boosting of voltage to meet effective grid synchronization. The output voltage and current under normal condition provided by Luo converter is illustrated in Figures 6(a) and 6(b). It is noticed that with the adoption of cascaded ANN MPPT controller, the Luo converter generates an enhanced voltage and current of 630 V and 10 A after 0.15 s.



(a) (b)

Figure 5. Solar panel (a) voltage and (b) current waveform under normal condition



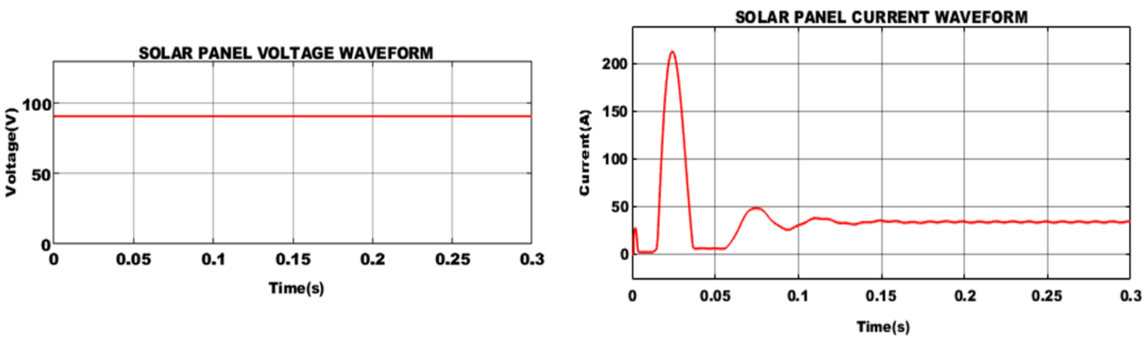
(a) (b)

Figure 6. Luo converter output: (a) voltage and (b) current waveform under normal condition

4.2. Case 2: Under partially shaded condition

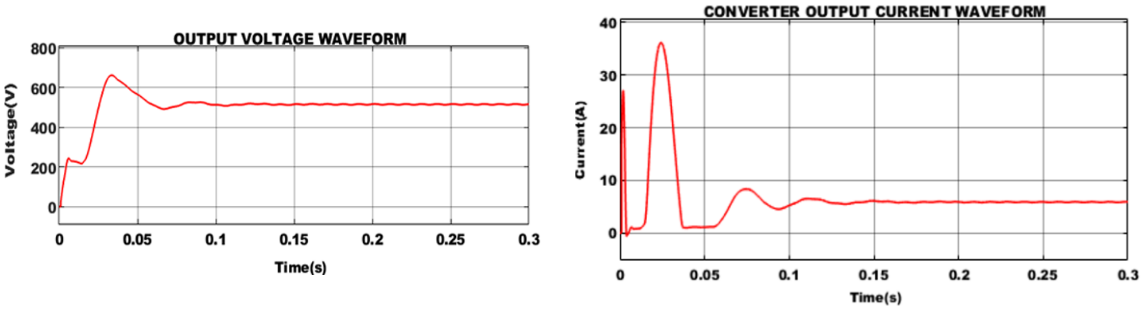
A PV voltage and current waveform is illustrated in Figures 7(a) and 7(b) under PSC. This condition is achieved by decreasing the intensity of any of the panels. It is observed that input power of 90 V and 48 A is produced by the solar PV system. As a consequence, Figure demonstrated the corresponding converter output under PSC. Since, PV arrays are exposed to varying irradiance levels under PSC because of non-uniform shading. Due to the modules' mismatch, less power is produced. But, the adoption of proposed ML based cascaded ANN MPPT controller for tracing optimal power, the Luo converter tends to produce an enhanced voltage of 530V with current value of 8 A after 0.1 s, as described in Figures 8(a) and 8(b).

The output grid voltage and current of 1Φ grid is illustrated in Figures 9(a) and 9(b). From the observation, a stabilized voltage of 200 V and current of 10 A is achieved without any distrotions. The quality of power and current flowing in the system is characterized by total harmonic current distortion as illustrated in Figure 10. It is observed that a minimized THD value of 2.9% is achieved by the proposed system with reduced harmonic content.



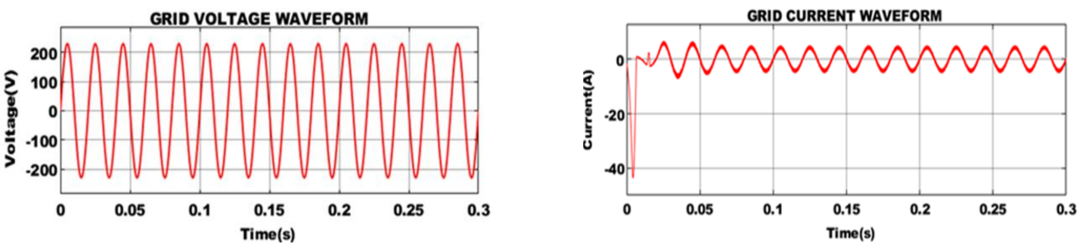
(a) (b)

Figure 7. Solar panel: (a) voltage under PSC and (b) current under PSC



(a) (b)

Figure 8. Luo converter output: (a) voltage under PSC and (b) current under PSC



(a) (b)

Figure 9. Waveforms of (a) grid voltage output and (b) grid current output

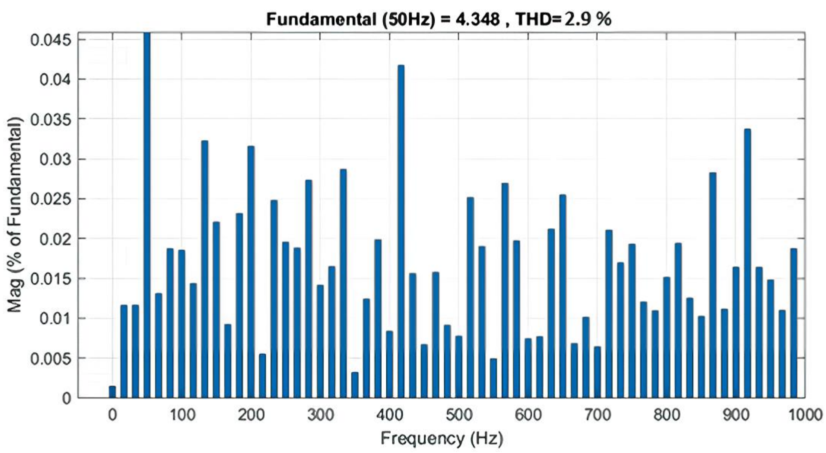
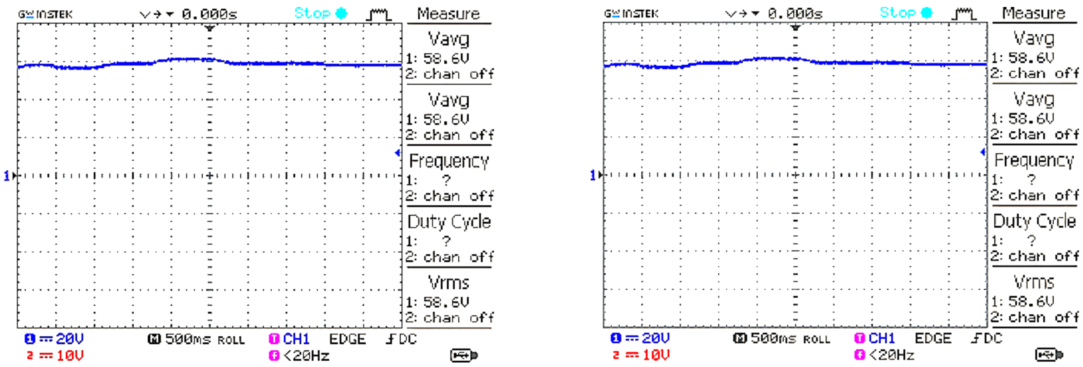


Figure 10. THD waveform for current

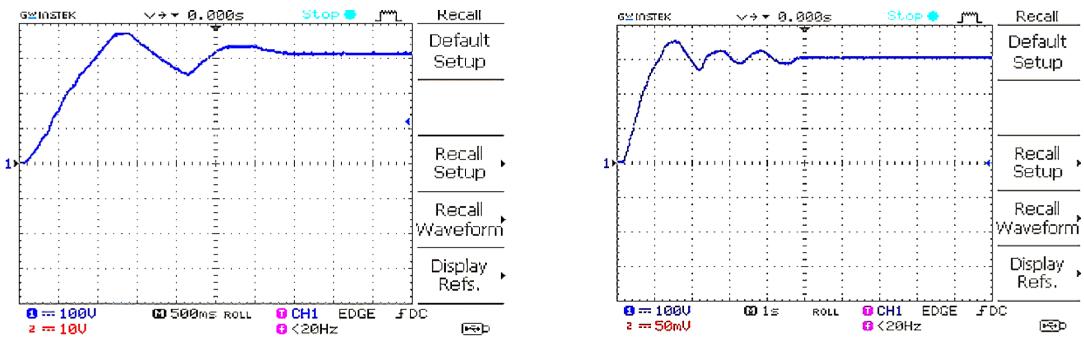
4.3. Hardware analysis

The maximum voltage generated by the panel is illustrated in Figures 11(a) and 11(b). The waveform exhibit variations in voltage over time due to factors like changes in sunlight intensity or shading and a constant of 60 V is achieved. The voltage waveform of a converter depending on switching frequency and machine learning based cascaded ANN MPPT control strategy is depicted in Figures 12(a) and 12(b). By adopting MPPT the proposed converter achieves 300 V steady supply.



(a) (b)

Figure 11. Input voltage: (a) solar panel 1 and (b) solar panel 2



(a) (b)

Figure 12. Converter performance: (a) converter voltage and (b) converter output using MPPT controller

The voltage waveform of the utility grid's in-phase component is a sinusoidal pattern that depicts the voltage provided by the grid. This can be observed in Figure 13. The waveform undergoes oscillations at the frequency of the grid and maintains a consistent magnitude. Correspondingly, the current waveform of the grid's in-phase component aligns with the voltage waveform but experiences a slight delay, commonly caused by the inductive properties of the grid.

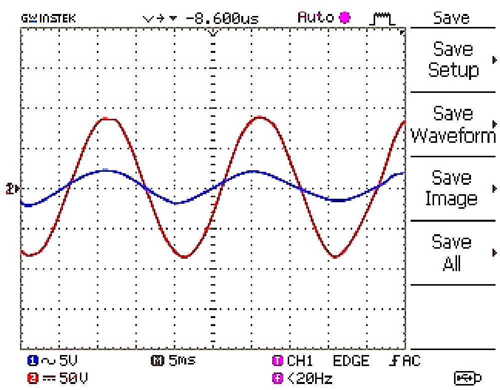


Figure 13. 1Φ grid output waveform

4.4. Efficiency calculation

The efficiency of Luo converter is assessed by contrasting its input and output power. In order to calculate Luo converter's efficiency more precisely, input power (P_{in}) and output power (P_{out}) are divided.

$$Efficiency = \left(\frac{P_{out}}{P_{in}}\right) \times 100\% \quad (7)$$

$$Efficiency\ Under\ Normal\ Condition = \left(\frac{630V \times 10A}{110V \times 58A}\right) \times 100\% = 98\%$$

$$Efficiency\ Under\ PSC = \left(\frac{530V \times 8A}{90V \times 48A}\right) \times 100\% = 98\%$$

An improved efficiency of 98% is obtained, thereby proving that the proposed Luo converter along with cascaded ANN controller provides optimal performance under different circumstances.

To validate the performance of the proposed DC-DC Luo converter, there is a need of comparison with the conventional converters. The efficiency and voltage gain of various converters are compared and arranged in Table 2 [26]–[28]. It is clearly observed that the proposed Luo converter achieves better values in both efficiency and voltage gain when compared to other converters. The tracking efficiency of various MPPT controller is contrasted with proposed cascaded ANN controller and listed in Table 3. It is evident that, the tracking efficiency achieved by MPPT controllers proposed in [29]–[31] low when contrasted with proposed MPPT approach as it results in better value of 98.77%.

Table 2. Efficiency comparison

Converter	Efficiency	Voltage Gain
Boost [26]	80%	$\frac{D}{(1-D)} = 1.5$
Buck-Boost [27]	85%	$\frac{D}{(1-D)} = 3$
SEPIC [28]	88.82%	$\frac{D}{(1-D)} = 8$
Proposed Luo	98%	$\frac{D}{(1-D)} = 10$

Table 3. Tracking Accuracy

Converter	Efficiency
Mohanty *et al.* [29]	97.78%
Sangwongwanich and Blaabjerg *et al.* [30]	97%
Goud *et al.* [31]	98.16%
Proposed cascaded ANN	98.77%

5. CONCLUSION

PV technology has been drawing attention because of its low-pollution operation and flexibility of installation. In order for PV systems to be effective, irradiation and temperature must be taken into account. Accordingly, partial shading reduces irradiation and reduces power generated when incident shadows are cast by surroundings. Hence, the proposed work utilizes ML based cascaded ANN system controls the Luo converter, forcing PV system to function at a MPP level in order to maximize efficiency. The adoption of cascaded ANN controller owes benefits like improved accuracy and faster response under varying circumstances and reduce losses. The optimal voltage obtained using cascaded ANN approach is transferred to Luo converter and controls the duty cycle for ensuring system to operate at MPP. The adoption of Luo converter in grid system provides improved grid stability, efficiency and reduced cost. The endorsement is carried out using MATLAB/Simulink and it is concluded that an improved efficiency value of 98% is obtained by adopting cascaded ANN controller with reduced THD value of 2.9% along with Voltage gain value of 1:10 respectively.

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