Simulation-Based Analysis of a Stand-Alone PV System Integrating Cúk Converter and Single-Phase SPWM Inverter

Mayuri Sunhare, Mayank Sunhare, Chandrakant Sharma

***Abstract**: This paper presents a simulation-based analysis of a standalone 1 kW photovoltaic (PV) energy system that integrates a Cuk DC–DC converter and a single-phase SPWM inverter for delivering high-quality AC output to residential and rural loads. The main objective is to enhance the efficiency and power quality of PV-based standalone systems through an optimized power conversion and control approach. To achieve this, the proposed system incorporates a Cúk converter configured with a digital Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm. This algorithm continuously adjusts the duty cycle of the converter to extract maximum available energy under varying solar irradiance and temperature conditions. The Cúk converter boosts the unregulated PV voltage to a constant 380 V DC, where a lithium-ion battery is connected to buffer surplus energy and ensure uninterrupted power during periods of low insolation. The regulated DC output feeds a single-phase full-bridge inverter employing sinusoidal pulse-width modulation (SPWM) with a unipolar switching strategy. This inverter generates a 230 V RMS, 50 Hz output with reduced harmonic content. An LC filter at the inverter output suppresses high-frequency switching harmonics, improving voltage waveform quality. The entire system is modelled and simulated in MATLAB/Simulink R2024b. Simulation results confirm that the proposed architecture maintains a stable DC-link voltage and produces a clean AC output. Total Harmonic Distortion (THD) values are observed to be 0.73% for voltage and 0.71% for current, validating compliance with IEEE Std. 519. This research highlights the effectiveness of combining Cúk converters with MPPT and SPWM-based inverters for standalone PV applications. The approach not only ensures efficient power conversion and low harmonic distortion but also demonstrates robustness under dynamic environmental conditions. The system is well-suited for off-grid and remote electrification scenarios where clean and reliable power is essential.*

***Keywords**: Standalone PV System, Cúk Converter, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), SPWM Inverter, Unipolar PWM, LC Filter, Total Harmonic Distortion (THD), Battery Energy Storage, MATLAB/Simulink.*

***Abbreviations*:**

PV: Photovoltaic
MPPT: Maximum Power Point Tracking
P&O: Perturb and Observe
SPWM: Sinusoidal Pulse Width Modulation
THD: Total Harmonic Distortion
LC Filter: Inductor-Capacitor Filter
DC: Direct Current
AC: Alternating Current
VSI: Voltage Source Inverter
FFT: Fast Fourier Transform
RMS: Root Mean Square

Manuscript received on 01 July 2025 | First Revised Manuscript received on 06 July 2025 | Second Revised Manuscript received on 11 July 2025 | Manuscript Accepted on 15 July 2025 | Manuscript published on 30 July 2025.

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I. INTRODUCTION

The rapid depletion of conventional fossil fuels and their associated greenhouse-gas emissions have intensified the global pursuit of clean, renewable energy sources. Solar energy, in particular, is abundant, inexhaustible, and free to harvest, making photovoltaic (PV) systems an attractive alternative for standalone power applications such as remote telecommunications, rural electrification, and emergency backup [1]. Key advantages of PV systems include minimal maintenance requirements, zero operational emissions, and a one-time capital investment with low lifetime operating costs.

However, PV panels exhibit highly non-linear current–voltage characteristics that vary with solar irradiance and temperature. To maximize energy extraction, a Maximum Power Point Tracking (MPPT) algorithm is employed in conjunction with a DC–DC converter stage. Among various topologies, the Cuk converter stands out for standalone PV–battery systems because it provides continuous input and output currents, low ripple, and inherent bidirectional power flow, enabling seamless charging and discharging of the battery [2]. Unlike boost or SEPIC converters—which either invert the output or suffer higher ripple—the Cúk topology uses a series coupling capacitor and two inductors to maintain low electromagnetic interference (EMI) and reduced component stress.

A battery energy storage unit is connected at the DC link to store excess PV energy and supply power during periods of low insolation. The combined PV–Cúk–battery arrangement ensures a regulated DC link voltage under varying load and environmental conditions. "Fig.1" illustrates the overall system architecture.

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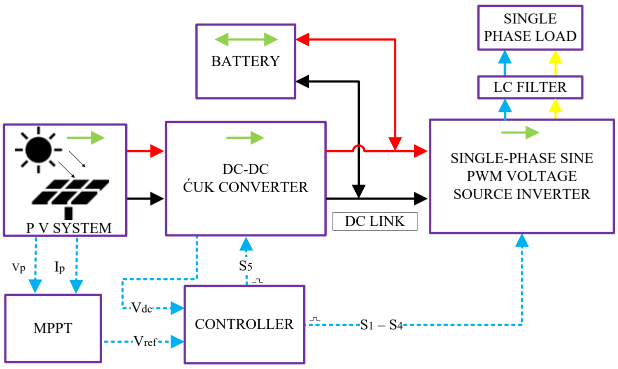
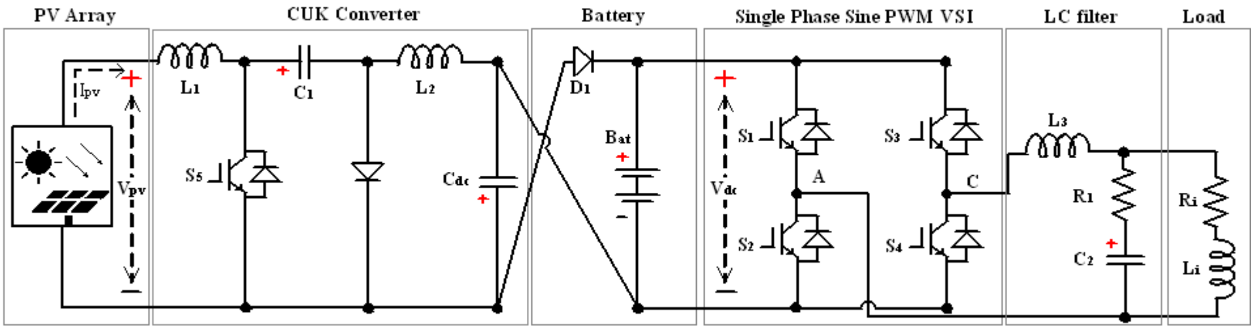


[Fig.1: System Architecture of Proposed Topology] [1]

On the AC side, a single-phase full-bridge inverter utilising Sinusoidal Pulse-Width Modulation (SPWM) is employed to generate a 230 V, 50 Hz output. The SPWM technique operates by comparing a high-frequency triangular carrier waveform with a sinusoidal reference signal, effectively controlling the switching of the inverter's power devices. This modulation strategy enables the synthesis of a high-fidelity output waveform with reduced harmonic distortion [3]. To further suppress the high-frequency switching components, an L–C output filter is incorporated, ensuring that the Total Harmonic Distortion (THD) remains below 5%, making the system suitable for powering sensitive standalone loads.

II. PROPOSED SYSTEM CONFIGURATION

The configuration of the proposed standalone photovoltaic (PV) power supply system is illustrated in "Fig. 2". The system architecture is designed to enable efficient solar energy extraction, energy storage management, and high-quality AC output for standalone applications. It consists of five main functional blocks:(A) a photovoltaic (PV) array with MPPT, (B) a Cúk DC–DC converter, (C) a battery energy–storage interface, (D) a single-phase SPWM voltage-source inverter (VSI), and (E) an L–C output filter feeding a resistive–inductive load.



[Fig.2: Block Diagram of the Standalone PV-Cuk- Battery- Inverter System]

A. PV Array and MPPT

The photovoltaic module produces a nonlinear voltage–current (V–I) output that is dependent on irradiance and ambient temperature. To ensure optimal energy harvesting under variable conditions, a digital perturb-and-observe (P&O) MPPT algorithm is employed. This algorithm periodically perturbs the PV operating voltage and monitors changes in output power to guide the converter's duty cycle toward the maximum power point (MPP). This closed-loop control enhances system efficiency and responsiveness in response to changing environmental conditions [4].

B. Cuk DC-DC Converter

The Cúk converter serves as a power conditioning interface between the PV source and the DC link. It utilizes two inductors (L_1 and L_2) and a coupling capacitor (C_1) to transfer energy with reduced ripple and continuous current on both input and output sides. Unlike traditional buck or boost converters, the Cuk topology is well-suited for PV applications due to its capability to both step up and regulate voltage, while reducing electromagnetic interference (EMI) and lowering stress on switching devices [5].

C. Battery Energy-Storage Interface

A lithium-ion battery is connected directly to the DC link via a bidirectional switch. When PV generation exceeds load demand, the battery absorbs excess energy; during low-insolation or high-load conditions, it discharges to support V_{dc}. Placing the battery at the DC link ensures fast transient response and safeguards the Cúk converter from overload [5].

D. Single-Phase SPWM Inverter

The DC link voltage is processed by a single-phase full-bridge voltage source inverter employing sinusoidal pulse-width modulation (SPWM). The SPWM technique involves comparing a sinusoidal reference waveform with a high-frequency triangular carrier to generate switching pulses for the inverter. This control method ensures that the output AC waveform closely follows a 230 V RMS, 50 Hz sinusoid with low total harmonic distortion (THD) and improved power quality.

E. L-C Output Filter

To suppress high-frequency switching harmonics generated by the inverter, an L–C filter, composed of an inductor (Lf) and a capacitor (Cf), is connected at the inverter output. The filter is designed with a cutoff frequency that lies between the inverter's carrier frequency and the fundamental frequency of the output waveform. This allows the fundamental component to pass while effectively attenuating higher-order harmonics, resulting in a clean sinusoidal voltage at the load terminals.

Retrieval Number:100.1/ijese.H261313080725
DOI:10.35940/ijese.H2613.13080725
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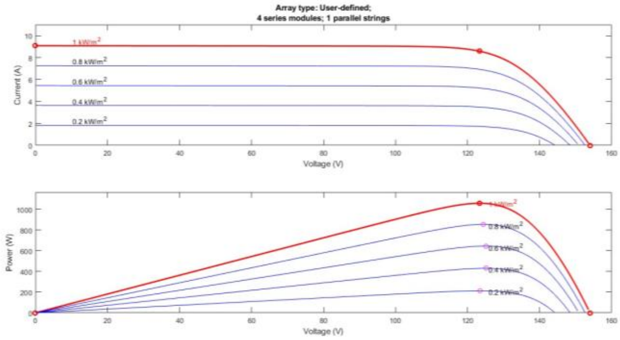
III. SYSTEM CONTROL

A. DC–DC Cúk Converter with MPPT Control

A 1 kW PV array—built from four Zshine PV-Tech ZX-M6-60-265-M modules in series and one string in parallel—supplies the Cúk converter. The PV Characteristics plots for different irradiations are shown in "Fig 3". Under Standard Test Conditions (1000 W/m², 25 °C), each module's short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum-power point values (V_{mpp}, I_{mpp}) are summarized in "Table I" [6].

To extract maximum power from the PV array, a digital perturb-and-observe (P&O) MPPT algorithm adjusts the converter's duty cycle D. At each sampling interval, the algorithm perturbs D and evaluates the change in PV



[Fig.3: PV Characteristics Plots for Different Irradiations (a) V-I Plot, (b) P-V Plot]

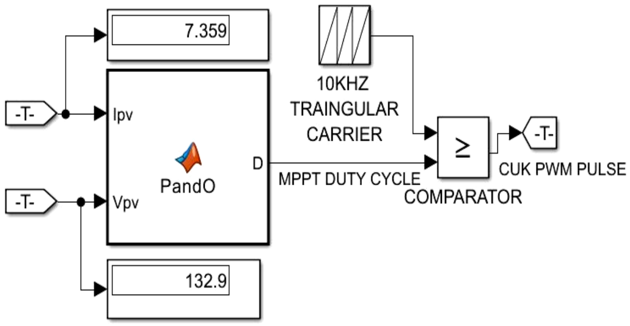
Power P_{pv}. If $\Delta P_{pv}/\Delta V_{pv}>0$, the perturbation continues in the same direction; otherwise, it reverses, providing a good compromise between tracking speed and steady-state ripple [6].

The sensed PV voltage, Vpv, and current, Ipv, are fed into the P&O block, which outputs the optimal duty command, D_{mppt}[7]. This command modulates a 10 kHz triangular carrier in a PWM comparator to generate the gate-drive signal for the main switch S_1("Fig. 4"). The Cúk stage then regulates the DC-link voltage V_{dc} above or below V_{pv} without inverting polarity, ensuring impedance matching between the PV array and inverter [8].

Key advantages of the Cúk topology include continuous input and output currents minimizing current ripple and EMI—and the use of a series coupling capacitor C_1 for energy transfer, which decouples the input from the output and reduces stress on inductors L_1 and L_2 [8]. Its capability to both step up and step down V_{pv} makes it particularly well suited for standalone PV applications where V_{pv} can vary widely.

B. Single-Phase SPWM Inverter

In a single-phase Sinusoidal Pulse-Width Modulation (SPWM) inverter, two sinusoidal reference signals, each of peak amplitude $V_{ref,pk}$ and frequency f_0, are compared against a high-frequency triangular carrier of peak $V_{tri,pk}$ and switching frequency f_{sw}. The comparator outputs generate the gate-drive pulses for the four bridge switches. The fundamental output frequency is set by f_0, while the RMS

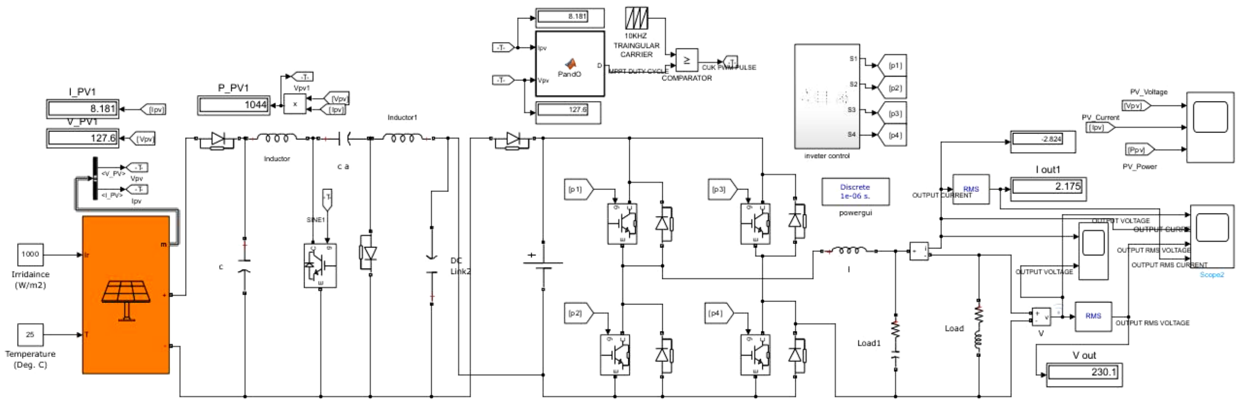


[Fig.4: P&O Based MPPT Controller for CÚK Converter]

The value of the fundamental voltage is proportional to the modulation index

$$m_a = \frac{V_{ref,pk}}{V_{tri,pk}}$$, and the harmonic spectrum is shaped primarily by f_{sw} [9].

A unipolar SPWM scheme is used to reduce low-order harmonics and EMI. In this configuration, two sinusoidal references, Vref, A(t) and Vref, B (t), are generated 180° out of phase. As shown in "Fig. 6", Each reference is independently compared with the same triangular carrier:



[Fig.5: Simulink Model of Proposed Topology]

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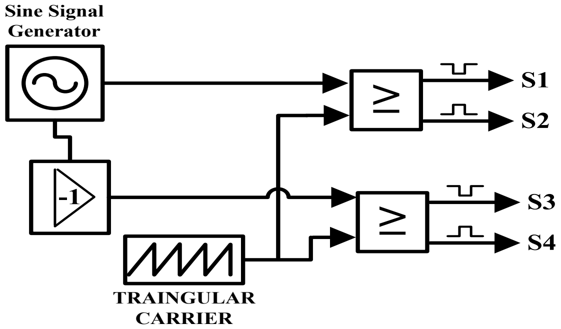
i. Phase A Half-Bridge (S_1/S_2):

S_1 *ON when* $V_{ref,A}(t) > V_{tri}(t)$; $S_2 = -S_1$.

ii. Phase B Half-Bridge (S_3/S_4):

S_3 *ON when* $V_{ref,B}(t) > V_{tri}(t)$; $S_4 = -S_3$.

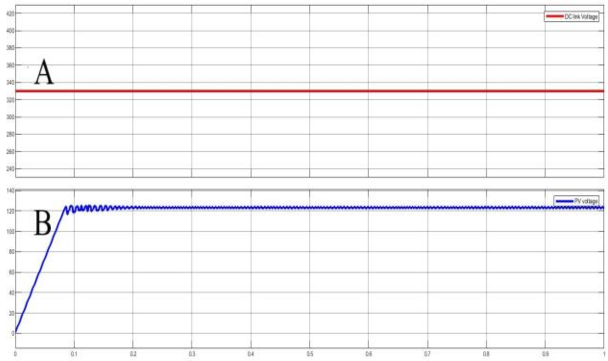
Because each half-bridge toggles separately, the output voltage waveform alternates between +Vdc, 0, and –Vdc, effectively halving the voltage stress on each switch and improving the harmonic profile compared to bipolar SPWM [10].



[Fig.6: Unipolar SPWM Control Technique for Single-Phase Inverter]

IV. SIMULATION RESULT AND DISCUSSIONS

The complete Stand-Alone PV System Integrating Cúk Converter and Single-Phase SPWM Inverter system, comprising the PV array, Cúk DC–DC converter under MPPT control, battery interface, full-bridge SPWM inverter, and L–C output filter, was modelled and simulated in MATLAB/Simulink R2024B (see "Fig 5"). All component and control parameters are summarized in "Table I".



[Fig.7: Waveform of (a) DC Link Voltage (CÚK Output Voltage) and (b) PV Voltage]

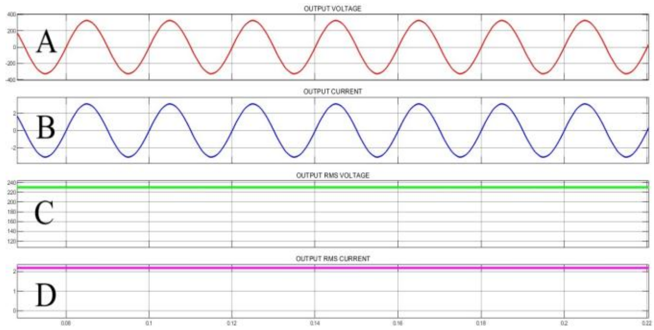
Simulations were carried out under standard test irradiance (1000 W/m², 25 °C). The Cúk stage regulates the DC-link to 380 V, feeding a composite load consisting of a series R–L branch (105.8 Ω + 1 mH) in parallel with a 1 kW constant-power load [10]. The MPPT algorithm updates the duty cycle at 1 kHz, while the SPWM inverter operates with a 10 kHz carrier frequency and 50 Hz sinusoidal reference (modulation index m_a = 0.8).

Under MPPT control, the 120 V PV array feeds the Cúk converter, which boosts and regulates the PV output to 380 V at the DC link ("Fig. 7"). A 380 V battery connects directly across this bus to buffer power during irradiance dips or load transients. The full-bridge inverter uses unipolar SPWM: two 50 Hz reference sinusoids, shifted by 180°, are each compared with a 10 kHz triangular carrier to generate the gate pulses for switches S_1–S_4 ("Fig. 9a–h"). An L–C filter following the inverter suppresses the high-frequency switching components, delivering a clean 230 Vrms, 50 Hz waveform to the 1 kW resistive–inductive load ("Fig. 7c").

A spectral analysis using Simulink's FFT tool at a modulation index m_a = 0.8 yields a voltage THD of 0.73% and a current THD of 0.71% (see "Fig. 10" and "Fig. 11"). Simulation results confirm that the L–C filter readily cleanses the unipolar SPWM output. The filtered voltage exhibits a THD below 5%, in compliance with IEEE Std. 519 guidelines [11].

Table I: Simulation Parameters

	Parameters	Value
PV ARRAY	Znshine-PV-tech-ZXM6-60-265-M	
	Open circuit voltage (Voc)	38.5 V
	Short-circuit current (Isc)	9.07 A
	Voltage at maximum power point (Vmp)	30.84 V
	Current at maximum power point (Imp)	8.59 A
	Maximum power/module	246.91 W
	Cells per module	60 Ncell
	Temperature coefficient of open-circuit voltage	-0.32%/deg.C
	Series modules	4
	Parallel modules	1
CÚK	Capacitor, C_1	1000 µf
	Inductor, L_1	1.056 mH
	Inductor, L_2	2.9 mH
	DC-link Capacitor (C_{dc})	36.5 µf
	DC-link voltage (V_{dc})	330 V
	Cuk switching frequency	10000 Hz
	Battery voltage (V_{bat})	330 V
INVERTER	Inverter amplitude modulation ratio, m_a=0.98/1	0.98
	Inverter frequency modulation ratio, m_f=5000/50	100
	Filter capacitor (C_2)	20 µf
	Filter inductor (L_3)	5 mH
	Inverter output voltage	230 V_{rms}
	RL Load, (R_i, L_i)	105.8 Ω, 1 mH



[Fig.8: SPWM Inverter Output Waveform (a) Output Voltage, (b) Output Current, (c) Output Rms Voltage, (d) Output Rms Current]

V. SIMULATION RESULT AND DISCUSSION

A standalone solar PV system integrating a Cuk converter and a single-phase SPWM inverter was modelled and simulated using MATLAB/Simulink R2024B. The complete system includes a photovoltaic array, a DC–DC Cúk converter

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DOI:10.35940/ijese.H2613.13080725
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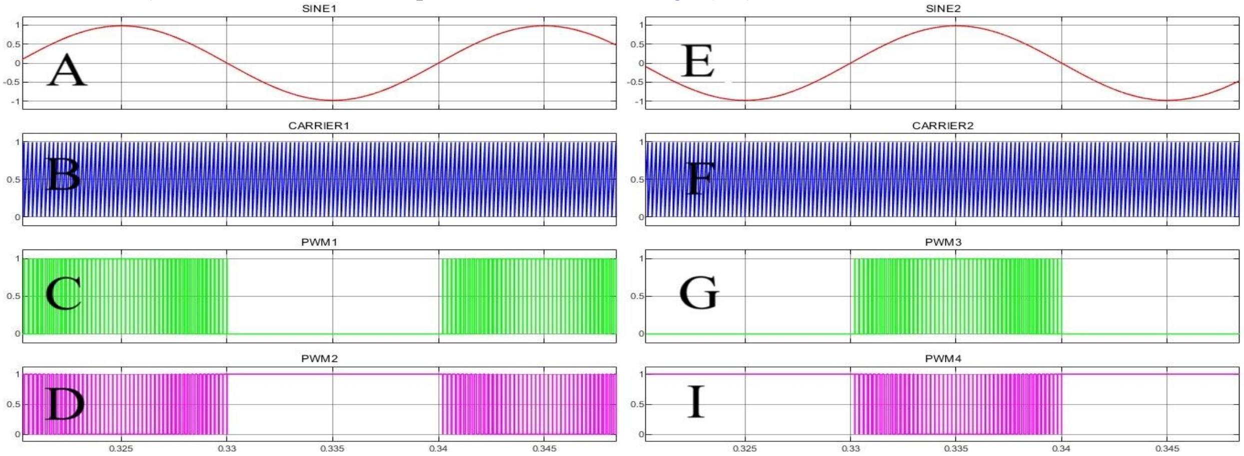
regulated by MPPT, a battery connected across the DC-link, a full-bridge SPWM inverter, and an L–C output filter, as illustrated in "Fig. 8". All simulation parameters and component values used are summarized in Table I.

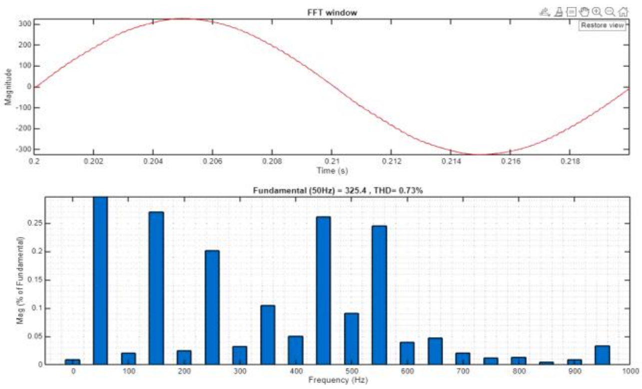
The simulation was conducted under standard test conditions, specifically at an irradiance of 1000 W/m² and a temperature of 25 °C. A 120 V PV source feeds the Cuk converter, which steps up the voltage to a regulated 380 V DC link. This voltage is maintained consistently to power a combined load comprising a resistive-inductive branch (105.8 Ω + 1 mH) and a 1 kW constant power load. The MPPT controller, based on the Perturb and Observe (P&O) algorithm, operates at 10 kHz and ensures maximum power extraction from the PV system.

A 380 V battery is connected directly to the DC bus to provide load support during transient conditions. The full-bridge inverter is modulated using a unipolar SPWM technique, where two sinusoidal reference signals of 50 Hz (180° phase-shifted) are compared with a 5 kHz triangular carrier to generate the gate pulses for switches S_1–S_4. The generated gate pulses and modulation signals are shown in "Fig.9(a–i)".



[Fig.9: (a) Sinusoidal Reference Wave, (b) Carrier Frequency Wave, (c) SPWM for Switch S1, (d) SPWM for Switch S2, (e) 180˚ Phase Shift Sinusoidal Reference Wave, (f) Carrier Frequency Wave, (g) SPWM for Switch S3, (i) SPWM for Switch S4]

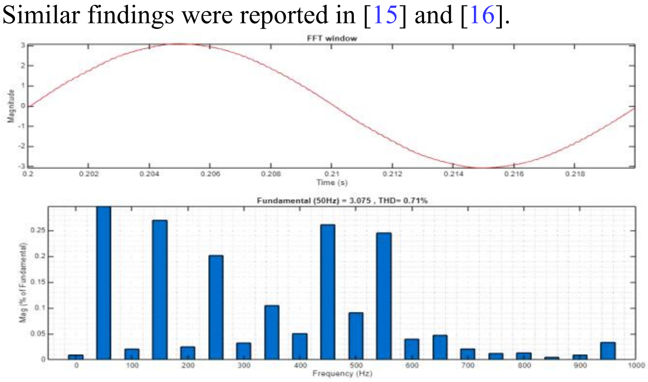
To suppress high-frequency harmonics produced during the switching operation, an L–C filter is deployed at the inverter output. After filtering, the inverter delivers a stable 230 V RMS, 50 Hz AC voltage to the load, as shown in "Fig. 7(c)". A Fast Fourier Transform (FFT) analysis was conducted in Simulink to evaluate harmonic performance. At a modulation index of ma=0.98, the output voltage and current waveforms exhibit total harmonic distortion (THD) values of **0.73 %** and **0.71 %**, respectively, "Fig. 10" and "Fig. 11". These values are well below the 5 % THD threshold recommended by **IEEE Standard 519**, confirming that the unipolar SPWM inverter, when combined with a properly designed L–C filter, provides high-quality power output suitable for standalone applications.



[Fig.10: Output Voltage FFT Analysis with ma=0.98 is 0.73% THD]

VI. CONCLUSION

This paper presents a simulation-based analysis of a standalone solar photovoltaic system incorporating a Cúk DC–DC converter and a single-phase SPWM inverter for residential and remote applications. The Perturb and Observe (P&O) MPPT algorithm efficiently tracks the maximum power point of the PV array under varying solar conditions [12], ensuring optimal power extraction. The Cúk converter maintains a regulated DC link voltage of 380 V while interfacing with a 120 V PV input and a battery energy storage system [13]. The inverter, driven by a unipolar SPWM control strategy, delivers a sinusoidal 230 V RMS output with minimal distortion, as demonstrated in [14]. Similar findings were reported in [15] and [16].



[Fig. 11: Output Current FFT Analysis with ma=0.98 is 0.71% THD]

Simulation results confirm the viability of the proposed configuration, with total harmonic distortion (THD)

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levels of 0.73% for the output voltage and 0.71% for the current remaining well below the 5% threshold set by IEEE Standard 519. The L–C filter effectively attenuates switching harmonics, ensuring the power quality meets grid-independent standards. The proposed architecture thus provides a reliable and efficient solution for standalone PV applications that require a clean AC output.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to my brother, Mr. Mayank Sunhare, for his invaluable guidance, unwavering support, and steadfast encouragement throughout this research. His insights and motivation have significantly contributed to shaping the direction and outcome of this work. I am deeply thankful to my Ph.D. supervisor, Prof. C. K. Sharma**,** for his exemplary mentorship, scholarly advice, and unwavering support. His constructive feedback and academic rigour have been instrumental in the successful completion of this research endeavour. I would also like to extend my sincere appreciation to my family and friends for their enduring encouragement, patience, and moral support, all of which have been essential to my academic progress and personal growth during this journey.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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