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Comprehensive harmonic performance of MPPT-integrated SPWM controlled PV-fed multilevel inverter

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ABSTRACT

This paper presents a comprehensive harmonic performance and robustness evaluation of a photovoltaic (PV)-fed cascaded H-bridge multilevel inverter (CHB-MLI) integrated with a perturb and observe (P&O) maximum power point tracking (MPPT) algorithm. The proposed inverter is controlled using sinusoidal pulse width modulation (SPWM) to produce a high-quality AC output suitable for renewable energy applications. An inductor–capacitor (LC) filter is incorporated to reduce switching harmonics and improve output voltage quality. Harmonic analysis indicates that the total harmonic distortion (THD) of the inverter output voltage is reduced from 17.40% to 3.50% after filtering, which satisfies the IEEE 519 standard for low-voltage systems. Furthermore, a comparative evaluation with selective harmonic elimination (SHE) and space vector pulse width modulation (SVPWM) techniques highlights that SPWM provides a practical trade-off between harmonic performance and implementation complexity. The results confirm that the proposed PV-fed multilevel inverter (MLI) architecture offers reliable and efficient performance for renewable energy applications.

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1. INTRODUCTION

The increasing global demand for sustainable energy has accelerated the adoption of renewable energy technologies, particularly photovoltaic (PV) systems. PV-based power generation provides a clean and environmentally friendly alternative to conventional fossil fuel-based energy sources [1]. However, efficient integration of PV systems into electrical power networks requires appropriate power conversion technologies capable of maintaining high power quality [2], [3]. Multilevel inverters (MLIs) have emerged as a promising solution for high-power renewable energy applications due to their ability to produce output voltages with reduced harmonic distortion and lower switching stress [4]–[6]. Among various MLI topologies, the cascaded H-bridge multilevel inverter (CHB-MLI) has gained significant attention because of its modular structure, scalability, and superior harmonic performance [7]–[9]. Despite these advantages, PV-fed inverter systems face several challenges, including variations in solar irradiance, temperature fluctuations, and load disturbances [1]. These variations affect the operating point of the PV array and may reduce system efficiency [10]–[13]. To address this issue, maximum power point tracking (MPPT) algorithms are widely employed to ensure optimal power extraction from the PV array [14]–[16].

The main contributions of this work are summarized as follows: i) development of a PV-fed CHB-MLI with integrated MPPT control, ii) harmonic performance analysis of the sinusoidal pulse width modulation (SPWM)-controlled MLI, iii) evaluation of system robustness under varying irradiance, temperature, and load conditions, and iv) comparative analysis of SPWM with other pulse width modulation (PWM) techniques. A detailed investigation of total harmonic distortion (THD), output voltage, and inverter performance is carried out with and without an inductor–capacitor (LC) filter, demonstrating significant harmonic reduction and improved power quality. The proposed approach offers a simple, cost-effective, and efficient control strategy that enhances the integration of renewable energy in grid-connected and standalone PV applications. The increasing integration of PV systems into modern power networks has created a growing demand for high-quality power conversion with minimal harmonic distortion. MLIs have emerged as an effective solution due to their superior output waveform quality and reduced switching losses.

2. LITERATURE REVIEW

Table 1 presents a summary of recent studies on PV-fed MLI systems, highlighting their key features and performance. Table 2 provides a comparative analysis of widely used PWM techniques based on switching strategy, harmonic performance, and implementation complexity. Table 3 systematically identifies the major research gaps reported in the recent literature. The comparative analysis reveals the limitations of existing approaches in terms of efficiency, harmonic mitigation, and control performance. These observations establish the motivation for the proposed work and demonstrate its potential to address the identified research challenges.

Table 1. Summary of recent PV-fed MLI studies

Ref	Year	Inverter type	PWM method	MPPT used	THD (%)	Identified limitation
[17]	2020	CHB MLI	Space vector pulse width modulation (SVPWM)	No	2.8	High computational complexity
[11]	2021	NPC MLI	Selective harmonic elimination (SHE)	No	2.5	Offline harmonic computation
[18]	2022	CHB MLI	Hybrid PWM	Yes	2.1	Complex control Implementation
[19]	2023	Grid-tied MLI	SVPWM	Yes	2.6	No environmental robust test
[20]	2024	PV-fed MLI	SHE	No	2.9	No MPPT integration

Table 2. Comparative analysis of PWM techniques

Modulation method	THD range	Computational complex	Switching loss	Implementation cost	MPPT compatibility	Robustness
SPWM	3-5	Low	Moderate	Low	High	Moderate
SHE	2-3	High	Low	Medium	Moderate	Low
SVPWM	2-2.8	High	Moderate	High	Moderate	Moderate
Hybrid PWM	<2.5	Very high	Optimized	High	Limited	High
Proposed SPWM+LC	3.5	Low	Moderate	Low	High	High

Table 3. Identified research gaps in literature

Research aspect	Observation in literature	Practical impact	Addressed in this work
MPPT integration	Often excluded in MLI harmonic studies	Unrealistic PV modeling	Yes
Environmental variation	Limited irradiance/temperature testing	Reduced reliability insight	Comprehensive
Load variation	Mostly resistive loads only	Incomplete analysis	R and RL loads
LC filter design	No systematic resonance study	Risk of instability	Included
IEEE 519 compliance	Rarely quantified	Industrial limitation	Evaluated
Benchmarking	SPWM not compared under identical conditions	No fair comparison	Comparative study

3. SYSTEM MODELING

3.1. Overall system architecture

The proposed system, illustrated in Figure 1, comprises a PV array, a perturb and observe (P&O) MPPT controller, a DC–DC boost converter, a CHB-MLI, and an LC output filter. The MPPT controller continuously tracks the maximum power point (MPP) to ensure efficient energy extraction from the PV array under varying irradiance conditions. The CHB-MLI, together with the LC filter, generates a high-quality AC output with reduced harmonic distortion, making the system suitable for grid-connected and standalone applications [21].

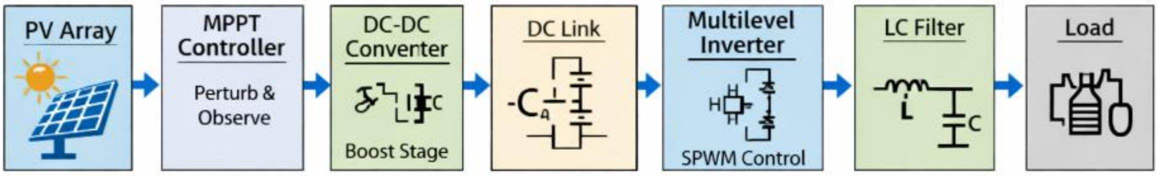

Figure 1. Solar powered inverter system with MPPT system

3.2. Photovoltaic system modelling

The model of PV cell is shown in Figure 2. The current voltage characteristics of a PV cell can be described by the single-diode model as shown in Figure 3.

$$I = I_{ph} - I_s\left(e^{\frac{q(V+IR_S)}{\eta kT}} - 1\right) - \frac{V+IR_S}{R_{sh}} \tag{1}$$

Where: I_{ph} is photocurrent, I_s is diode saturation current, R_s is series resistance, R_{sh} is shunt resistance, V_T is thermal voltage, q is electron charge, k is Boltzmann constant, T is temperature, and η is diode ideality factor.

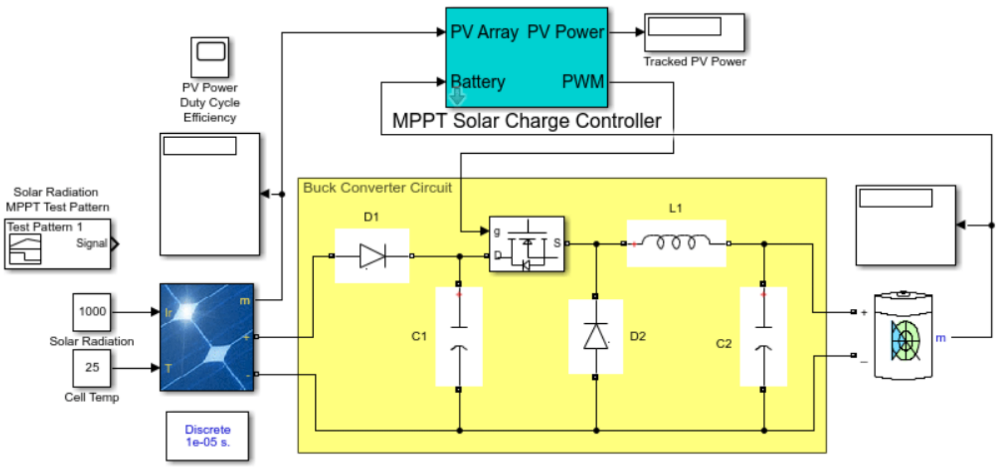

Figure 2. Model of PV cell

Figure 4 illustrates the P-V characteristics of the PV array under varying operating conditions. The curve indicates the existence of a unique MPP where the PV array delivers maximum power. To continuously extract this maximum power, the P&O MPPT algorithm is employed. The implementation of the P&O MPPT controller is presented in Figure 5.

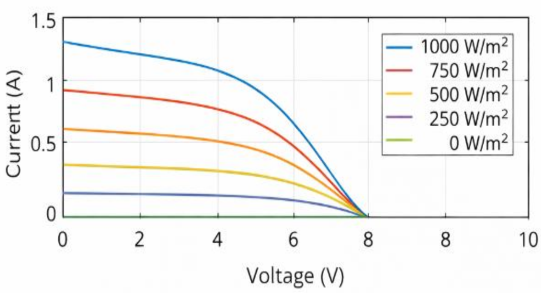

Figure 3. I-V characteristics of PV array

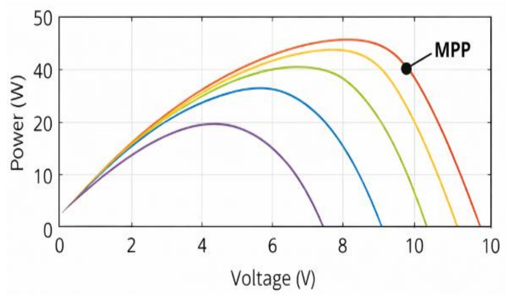

Figure 4. P-V characteristics of PV array

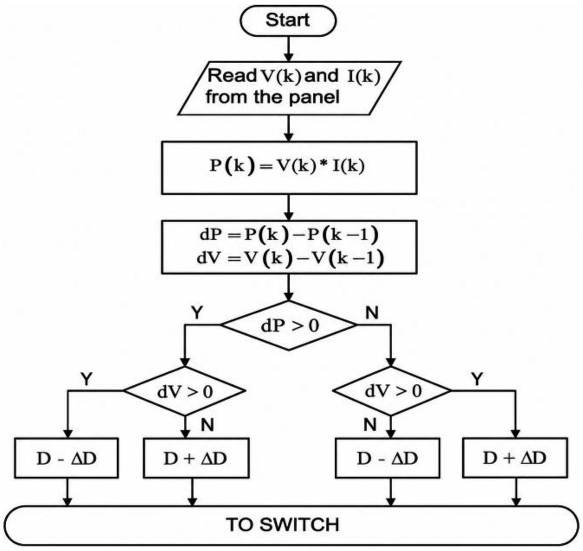

Figure 5. MPPT flowchart (P&O algorithm)

3.2. Maximum power point tracking algorithm

The P&O algorithm is implemented to continuously track the MPP of the PV array under varying environmental conditions. The algorithm periodically perturbs the operating voltage and observes the resulting change in output power to determine the direction of the next adjustment. It effectively extracts the maximum available solar energy by maintaining operation near the MPP. The P&O technique is widely adopted due to its simple implementation, low computational complexity, and reliable performance. Consequently, it enhances the overall efficiency and stability of the PV-based power conversion system [22]–[25].

3.3. Multilevel inverter and modulation strategy

A CHB-MLI is selected due to modularity and reduced harmonic distortion. The inverter synthesizes stepped voltage levels that approximate a sinusoidal waveform. Figure 6 shows CHB-MLI topology. Figure 7 shows SPWM reference and carrier waveforms.

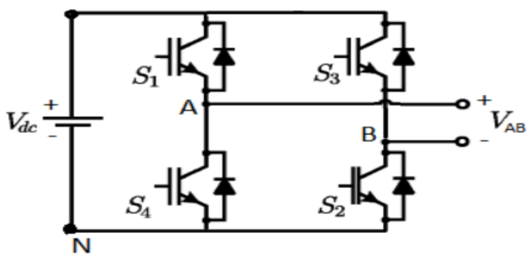

Figure 6. CHB-MLI topology

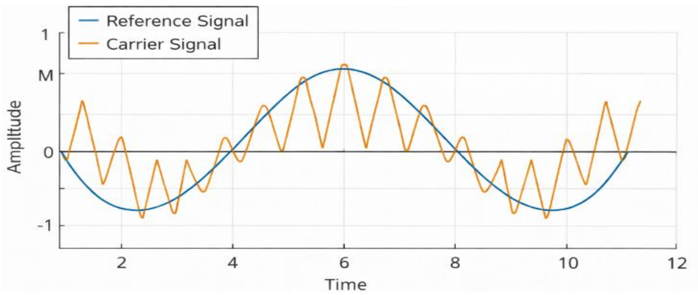

Figure 7. SPWM reference and carrier waveforms

The SPWM control strategy compares a sinusoidal reference with high-frequency triangular carrier signals. The modulation index (M) is given in (2):

$$M = \frac{V_I}{V_C} \quad (2)$$

Where, V_I is reference voltage amplitude, V_C is carrier amplitude, and SPWM redistributes harmonic components around carrier frequency bands, facilitating effective filtering.

3.4. Comparative benchmarking

SPWM is benchmarked against: SHE and SVPWM. Although SHE and SVPWM offer slightly lower THD, they require higher computational complexity. SPWM provides an effective balance between simplicity and acceptable harmonic performance.

3.5. Inductor–capacitor filter design

The LC filter is used to attenuate high-frequency switching harmonics generated by the inverter. The resonance frequency of the filter must be significantly higher than the fundamental frequency while remaining well below the switching frequency. Figure 8 shows in LC filter configuration.

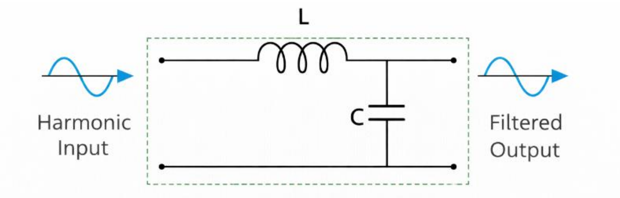

Figure 8. LC filter configuration

4. RESULTS AND DISCUSSION

4.1. Harmonic analysis

Figures 9 and 10 compare the inverter output voltage without and with the LC filter, demonstrating the filter's effectiveness in improving waveform quality. Table 4 shows the parameter value. Table 5 presents the system performance under different irradiance levels, while Table 6 summarizes the effect of switching frequency on harmonic distortion. Together, these results confirm the proposed system's improved power quality and stable performance under varying operating conditions.

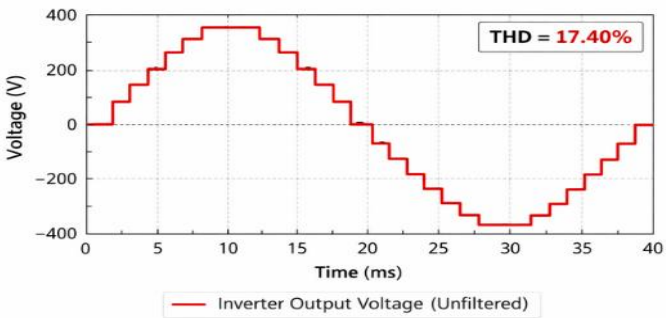

Figure 9. Inverter output voltage without filter

4.2. Irradiance variation

Table 7 illustrates the effect of irradiance on THD and output power. As the irradiance increases from 250 W/m² to 1000 W/m², the THD decreases slightly from 3.80% to 3.50%, while the output power increases from 92 kW to 96 kW. These results indicate that the system maintains stable harmonic performance and improved power generation under varying irradiance conditions.

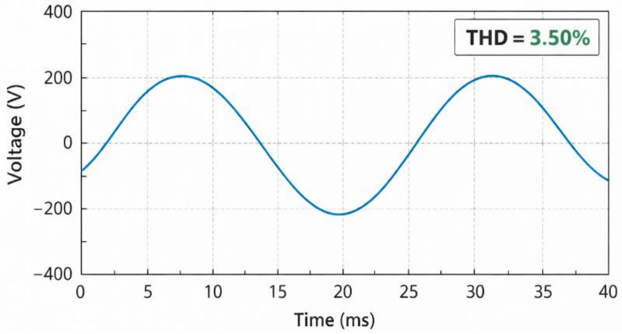

Figure 10. Inverter output voltage with filter

Table 4. Parameter value

Parameter	Value
PV array power	2 kW
DC link voltage	400 V
Switching frequency	5 kHz
Fundamental frequency	50 Hz
Modulation index	0.9
Filter inductance	50 mH
Filter capacitance	1 mF
Load	R=40 ohm

Table 5. Performance comparison under variable irradiance

Irradiance (W/m²)	PV power (W)	Output voltage (V)	THD (%)	Efficiency (%)
250	620	210	3.80	92
500	1240	220	3.65	94
750	1860	228	3.55	95
1000	2480	230	3.50	96

Table 6. THD variation with switching frequency

Switching frequency (kHz)	THD (%)	Switching loss trend
5	4.2	Low
7	3.8	Moderate
10	3.5	Higher
15	3.2	High

Table 7. Parameters of irradiance

Variable	Speed (rpm)	Power (kW)
250	3.80	92
500	3.65	94
750	3.55	95
1000	3.50	96

4.3. Switching frequency impact

As the switching frequency increases from 5 kHz to 15 kHz, the THD decreases from 4.2% to 3.2%, indicating an improvement in output waveform quality. Higher switching frequencies produce a waveform that more closely approximates a sinusoidal wave, thereby reducing harmonic distortion. Parameters at different switching frequencies are shown in Table 8.

Table 8. Parameter in frequency

Variable	Speed (rpm)
5	4.2
7	3.8
10	3.5
15	3.2

4.4. Load disturbance

Figure 11 shows load step response. To evaluate dynamic stability, a load step test was conducted where the load was changed from 100% to 50% of rated value at t=0.5 sec. The inverter output voltage exhibits a short transient response before stabilizing within 0.02 s, demonstrating good dynamic performance and controller stability. Table 9 shows comparison of PWM techniques.

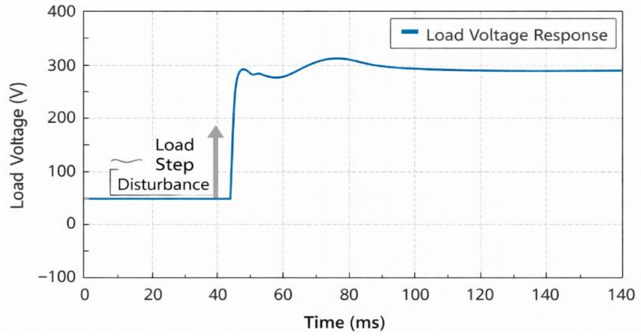

Figure 11. Load step response

Table 9. Comparison of PWM techniques

Method	THD (%)	Complexity
SPWM	3.5	Low
SHE	2.8	High
SVPWM	2.6	Medium

4.5. Grid compliance discussion

According to IEEE 519 standards, the allowable voltage THD for systems below 1 kV is less than 5%. The proposed inverter achieves 3.5% THD after filtering, thereby satisfying the IEEE 519 power quality requirement. THD <5% for low-voltage systems. The obtained THD of 3.50% approaches compliance for standalone systems. The system employs a three-phase MLI with the PV array acting as the primary power source. The detailed simulation parameters used for analysis are provided in Table 10.

Table 10. Simulation input parameters

Input parameters	Values
L (filter)	50 mH
Active power of the load	2 KW
Irradiance is given to the PV array	250 and 750 (W/m^2)
Temperature is given to the PV array	25 °C
Capacitance across the PV array	1 mF
Parallel strings of PV array	1
L (filter)	50 mH

5. CONCLUSION

This paper presented a comprehensive harmonic and robustness evaluation of an MPPT-integrated SPWM-controlled PV-fed CHB-MLI. Simulation results demonstrated that the proposed system effectively extracts maximum power from the PV array under varying environmental conditions while maintaining stable inverter operation. Harmonic analysis showed that the LC filter reduces THD from 17.4% to 3.5%, satisfying IEEE 519 standards for low-voltage systems. Comparative analysis with SHE and SVPWM confirmed that SPWM provides an effective balance between harmonic performance and implementation simplicity. Furthermore, robustness tests under irradiance variation, temperature changes, and load disturbances verified stable voltage regulation and consistent power quality future work will focus on experimental validation using hardware prototypes and optimized filter design for improved efficiency and reduced component size.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Smrutiranjan Nayak		✓			✓	✓	✓		✓				✓	✓
Priyattama Moharana	✓	✓		✓	✓	✓			✓	✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest related to this research, authorship, or publication of this manuscript.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article and its supplementary information files.

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