



Comparative Evaluation of Classical And Two-Phase Interleaved Boost Stages For 1 Kw Residential Photovoltaic Grid Interconnection

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ABSTRACT

Two-stage residential solar conditioning systems isolate maximum power tracking from low-frequency utility voltage fluctuations. This paper evaluates the electro-thermal and harmonic interactions of a 1 kW, 100 V array stepping up to a 400 V intermediate link connected to a 230 V, 50 Hz utility grid. This paper compares a classical boost stage directly against a symmetrical two-phase interleaved boost converter (IBC) implementing Intelligent MPPT algorithm using Fuzzy logic control (FLC). Both circuits are formulated via switched state-space representations and verified against closed-loop controls featuring stationary-frame proportional-resonant (PR) grid current tracking. Although the peak-to-peak 100 Hz voltage ripple experienced by the intermediate 400 V capacitor is 15.9 V due to single-phase power pulsation, the high-frequency current stress on the capacitor is reduced by 42.3% (from 4.33 A to 2.50 A) by interleaving. Also, active switch conduction dissipation is reduced from 6.00 W to 3.01 W, and the input current ripple goes down from 26.67% to 7.42%. This completely satisfies the criteria of IEEE 1547-2018 under the same magnetic volume constraints, since the resultant decrease in DC-link high-frequency harmonics results in a grid current total harmonic distortion (THD) of 1.62% as opposed to 2.84% in the conventional architecture.

Keywords: Interleaved Boost Converter, Fuzzy Logic Control, Harmonic Mitigation, Grid Code Compliance, Proportional-Resonant Control.

1. INTRODUCTION

Two-stage configurations dominate low-power (1 kW to 5 kW) grid-tied residential PV generation [1–3]. Separating the power conversion into a DC-DC front end, and a DC-AC bridge at the back has a couple of advantages. The inverter regulates power quality, grid synchronization, and anti-islanding, while the DC-DC stage manages significant PV voltage variations brought on by temperature swings and shading [4, 5].

Traditional boost converters experience switch stress in step-up conversion ratios of 100 V to 400 V with a nominal duty cycle D of 0.75 [6]. The single power switch must carry the full 10 A string current when ON. PV panels are heavily loaded with ripple injection and thermal dissipation [7]. The high frequency ripple causes the solar cells to oscillate around its theoretical maximum power point (MPP) and thus reduces the continuous tracking efficiency. Single-phase inverters naturally cause a second-harmonic ($2\omega = 100$ Hz) power fluctuation on the intermediate DC rail [9–11]. Inverter pulse-width modulation (PWM) is disrupted by front-end high-frequency ripple and low-frequency variation, worsening grid-injected current harmonics [12, 13].

The drawbacks of these converters are overcome by the IBCs which are multiphase interleaved boost converters, by operating two or more identical branches shifted by 180° [14–17]. The effective ripple frequency and the ripple amplitude are reduced due to the cancellation of the input terminal [18, 19]. The effective ripple frequency can be doubled. In low-voltage residential arrays, precise experimental and analytical grounding is required due to the coupled influence of interleaving on capacitor lifetime, semiconductor loss distribution, and grid current distortion, despite its prevalence in high-power converters [20, 21].

A 1 kW 100 V photovoltaic system supplying a 230 V grid through either configuration is compared in this paper in detail, both analytically and numerically which primarily address:

1. Mathematical state modeling under continuous conduction mode (CCM).
2. Component-level loss partitioning across switches, freewheeling diodes, and inductors.

3. Evaluation of intermediate capacitor high-frequency RMS current stresses.
4. Implementation of Fuzzy logic Control (FLC) for duty command generation
5. Harmonics injection and grid code verification under IEEE 1547-2018 standards.

2. CONVERTER MODELING AND CONTROL STRATEGY

2.1 System Baseline

The operational parameters for the baseline residential installation are summarized in Table-1. The PV generator is rated at nominal standard test conditions (STC: 1000 W/m², 25°C). To achieve high efficiency and avoid overmodulation in the single-phase H-bridge VSI under a +10% grid overvoltage condition (V_g , max=230√2×1.1= 357.8V), the intermediate DC bus reference is set to $V_{dc}^*=400V$.

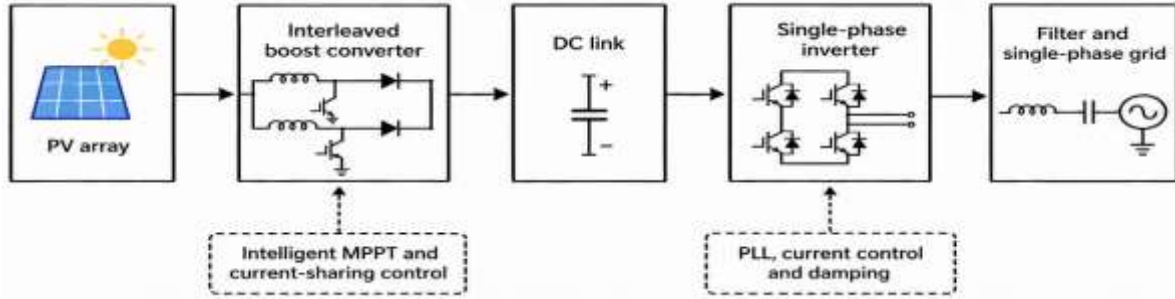


Fig. 1: One-line diagram of the PV 2 stage single phase grid integrating model

Table 1: System Design Parameters for 1 kW Setup

Parameter	Symbol	Value
Rated PV Power	P_{pv}	1000 W
Nominal Voltage at MPP	V_{mp}	100 V
Nominal Current at MPP	I_{mp}	10 A
DC-DC Switching Frequency	f_s	50 kHz
DC Bus Voltage Reference	V_{dc}^*	400 V
DC-Link Capacitor	C_{dc}	500 μF
Grid RMS Voltage / Frequency	V_g / f_g	230 V / 50 Hz
Inverter Switching Frequency	$f_{sw,inv}$	20 kHz
Grid Filter Inductance	L_g	3.5 mH

2.2 Classical Boost Dynamics

The classical boost converter consists of inductor L , active switch Q , and diode D . In continuous conduction mode (CCM), the circuit dynamics over a switching interval $T_s = 1/f_s$ with duty ratio

$$D = 1 - (V_{pv}/V_{dc}) = 0.75 \text{ are expressed as (1,5)}$$

For switch ON ($0 \leq t < DT_s$):

$$L \frac{di_L(t)}{dt} = V_{pv} - i_L(t)(R_{on} + r_L) \quad 1$$

$$C_{dc} \frac{dV_{dc}(t)}{dt} = -i_{inv}(t) \quad 2$$

For switch OFF ($DT_s \leq t < T_s$)

$$L \frac{di_L(t)}{dt} = V_{pv} - V_{dc}(t) - V_F - i_L(t)(R_D + r_L) \quad 3$$

$$C_{dc} \frac{dV_{dc}(t)}{dt} = i_L(t) - i_{inv}(t) \quad 4$$

where R_{on} is the channel on-resistance, r_L is winding ESR, V_F is diode forward drop, and R_D is diode dynamic resistance.

For $V_{PV}=100$ V, $V_{dc}= 400$ V, $D=0.75$, $F_s= 50$ KHZ and With $L = 750$ μH , the peak-to-peak inductor current ripple is:

$$\Delta I_L = (V_{pv} D) / (f_s L) = (100 \times 0.75) / (50000 \times 750 \times 10^{-6}) = 2.0 A. \quad 5$$

Because the PV array is tied directly in series with L, the string current experiences this full 2.0 A ripple (20% of I_{mp}).

2.3 Two-Phase Interleaved Boost Converter (IBC)

The two-phase IBC connects two identical boost stages in parallel across the input source and DC-link bus. Gate drive signals for switches Q1 and Q2 are phase-shifted by $\phi = 180^\circ \cdot (T_s/2)$. The total input current is (6)

$$i_{in}(t) = i_{L1}(t) + i_{L2}(t). \quad 6$$

Each phase carries an average current of $I_{mp}/2 = 5A$. For $D > 0.5$, switch ON periods overlap during interval $(2D-1)T_s$. With branch inductance $L_{ph} = 375 \mu H$ and $D = 0.75$, the net input ripple is (7)

$$\Delta I_{in,ibc} = \frac{V_{pv}(2D-1)}{f_s L_{ph} D} = \frac{V_{dc}(1-D)(2D-1)}{f_s L_{ph}} = \frac{100 \times (1.5-1)}{50 \times 10^3 \times 375 \times 10^{-6} \times 0.75} = 0.711 A \quad 7$$

The ripple attenuation ratio between the interleaved Conventional topologies is (8)

$$K_{ripple}(D) = \frac{\Delta I_{in,ibc}}{\Delta I_{L,ph}} = \frac{(2D-1)}{D} \text{ (for } D > 0.5) \quad 8$$

At $D=0.75$, $K_{ripple} = 0.5/0.75 = 0.667$. Because the individual branch inductance is halved while the effective ripple frequency doubles ($2f_s = 100$ kHz), the total high frequency current drawn from the PV array decreases drastically.

2.4 Intermediate Bus and Inverter Control

Single-phase utility injection incurs an unavoidable power fluctuation at twice the fundamental grid frequency ($2\omega = 100$ Hz) (9)

$$p_g(t) = 2V_g I_g \sin^2(\omega t) = P_{avg} - P_{avg} \cos(2\omega t) \quad 9$$

The DC-link capacitor must absorb this fluctuating power shown in (10)

$$\Delta V_{dc,2\omega} = \frac{P_{pv}}{\omega C_{dc} V_{dc}} = \frac{1000}{2\pi \times 50 \times 500 \times 10^{-6} \times 400} = 15.91V \quad 10$$

(3.98% low-frequency ripple).

To ensure pure current injection despite this ripple, we implement a stationary-frame proportional-resonant (PR) current controller shown in Fig-2 and its transfer function indicated in equation (11)

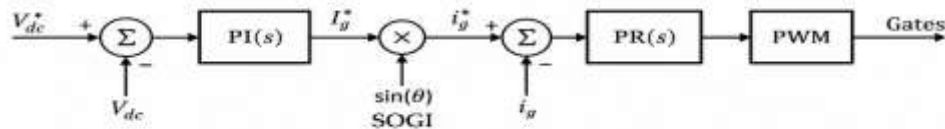


Fig. 2: Dual-loop control structure with outer voltage loop and inner PR current controller.

$$G_{PR}(s) = K_p + \sum_{h=1,3,5,7} \frac{2K_{ih}\omega_c s}{s^2 + 2\omega_c s + (h\omega_0)^2}, \text{ for } h = 1, 3, 5, 7 \quad 11$$

with $K_p = 18.5$, $K_i = 1200$, and cut-off bandwidth $\omega_c = 5$ rad/s.

3. CONVERTER LOSS AND RIPPLE ANALYSIS

3.1 Semiconductor Losses

3.1.1 MOSFET Conduction Loss

Conduction dissipation scales quadratically with RMS device current: $P_{cond,Q} = I_{Q,rms}^2 R_{on}$

For the classical boost converter: $I_{Q,rms,conv} = I_{in} \sqrt{D} = 10 \times \sqrt{0.75} = 8.660 A$.

For each leg of the 2-phase IBC: $I_{Q,rms,ibc} = \frac{I_{in}}{2} \sqrt{D} = 5 \times \sqrt{0.75} = 4.330 A$.

Summing both switches in the IBC:

$$P_{cond,Q,ibc} = 2 \times (4.33^2 R_{on}) = 2 \times \left(\frac{I_{in}}{2} \right)^2 D R_{on} = \frac{1}{2} P_{cond,Q,conv} \quad 12$$

Interleaving cuts active switch conduction loss by exactly 50%.

3.1.2 MOSFET Switching Loss

Linear switching transition models yield (13)

$$P_{sw,Q} = f_s V_{dc} I_{turn-off} \left(\frac{t_r + t_f}{2} \right) + \frac{1}{2} C_{oss} V_{dc}^2 f_s \quad 13$$

In the IBC, each leg interrupts half the current (5 A). Because switching losses scale linearly with current, the combined loss across both branches matches the single switch (14):

$$P_{sw,Q,ibc} = 2 \times \left[f_s V_{dc} \left(\frac{I_{in}}{2} \right) \left(\frac{t_r + t_f}{2} \right) \right] = P_{sw,Q,conv} \quad 14$$

3.2 Inductor Copper Losses

Winding copper losses are calculated in (15):

$$P_{cu} = I_{L,rms}^2 r_L = \left(I_{L,avg}^2 + \frac{\Delta I_L^2}{12} \right) r_L = 1.580W \quad 15$$

For the single 750 μ H inductor ($r_L \approx 50$ m Ω), Winding dissipation drops by 68.5%

3.3 Capacitor Current Stress

The high-frequency RMS ripple current through Cdc (16) directly influences internal self-heating and service lifetime:

$$I_{Cdc,rms} = \sqrt{I_{D,rms}^2 - I_{o,dc}^2} \quad 16$$

In the classical boost:

$$I_{D,rms,conv} = I_{in} \sqrt{1-D} = 10\sqrt{0.25} = 5.0A, \quad \text{giving,} \quad I_{Cdc,rms,conv} = \sqrt{5.0^2 - 2.5^2} = 4.330A$$

In the IBC, the two freewheeling intervals alternate:

$$I_{D,rms,ibc} = \sqrt{2 \times \left(\frac{I_{in}}{2} \right)^2 (1-D)} = \frac{10}{2} \sqrt{2 \times 0.25} = 3.536A$$

$$\text{giving: } I_{Cdc,rms,ibc} = \sqrt{3.536^2 - 2.5^2} = 2.500A$$

This 42.3% reduction in RMS ripple current allows replacement of wear-prone electrolytic capacitors with smaller polypropylene film types.

4. MPPT IMPLEMENTATION USING FUZZY LOGIC CONTROL

Fuzzy Logic Controllers (FLC) provide robust, model-free non-linear tracking capable of handling parameter variations without precise mathematical functions [22]. The standard FLC architecture accepts two input error variables computed at sample instant k: These inputs are mapped into linguistic fuzzy sets (Negative Big, Negative Small, Zero, Positive Small, Positive Big) via triangular or Gaussian membership functions. An inference engine executes rule bases (e.g., 'IF E is PB and CE is ZE, THEN ΔD is PB') shown in Table-2 and computes a crisp duty command through center-of-gravity defuzzification shown in Fig. 3. FLC delivers superior transient speed and minimal oscillation for power tracking.

Table- 2: Fuzzy-Controller rule matrix for duty cycle Generation

$\Delta P \backslash \Delta V$	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZE	ZE
NM	PB	PM	PM	PS	ZE	ZE	NS
NS	PM	PM	PS	ZE	NS	NM	NM
ZE	PM	PS	ZE	ZE	ZE	NS	NM
PS	PS	ZE	NS	ZE	NS	NM	NM
PM	ZE	ZE	NM	NS	NM	NM	NB
PB	ZE	NS	NM	NM	NB	NB	NB

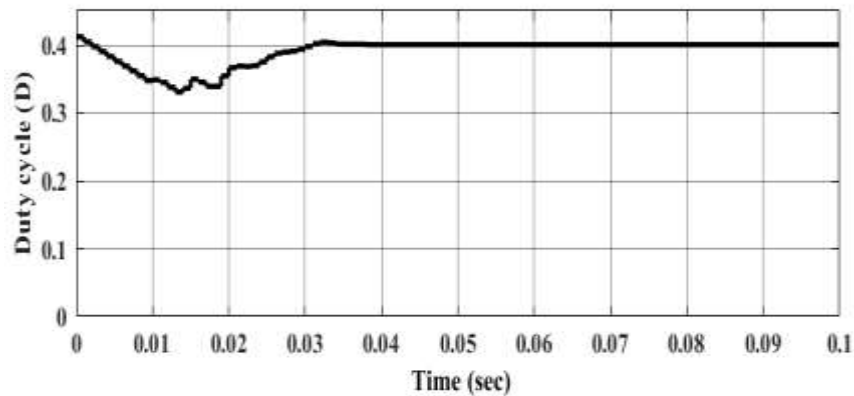


Fig. 3 Duty generated by FLC for DC-DC converter

5. SIMULATION RESULTS AND VERIFICATION

"The overall 1 kW grid-tied PV architecture was modelled in MATLAB using the stiff ode23tb solver at a discrete step size of 50 ns, setting the switch on-state resistance $R_{on} = 80 \text{ m}\Omega$. The comparative evaluation, supported by simulation waveforms across Sections 5.1 to 5.4, and quantitatively summarized in Table 3.

5.1 DC Bus and Grid side Measurements

The DC-bus and grid-side responses Fig.4 & Fig.5 indicates stable operation of both converter configurations, with the two-phase interleaved boost converter exhibiting a slightly improved DC-link performance compared with the classical boost converter. The DC-bus voltage remains regulated around its reference value in both cases, while the interleaved structure shows a marginally lower voltage ripple, indicating better input-power smoothing. The grid side voltage is almost sinusoidal wave form which confirms that the inverter and utility supply are synchronized in the correct manner as shown in Fig. 6. The two-phase IBC has a smoother current waveform with less ripple and less distortion than the classical boost topology. This is shown in Fig. 7 & Fig. 8 which compares the injected grid currents. The normalized grid voltage and current waveforms also confirm this improvement, showing the operation with a power factor very close to unity, where the voltage and current are almost in phase for both systems. Improved current quality and more efficient power transfer to the grid are indicated by the interleaved converter's closer waveform agreement. Overall, the results confirm that interleaving improves DC-link stability and grid-side current quality without adversely affecting grid synchronization.

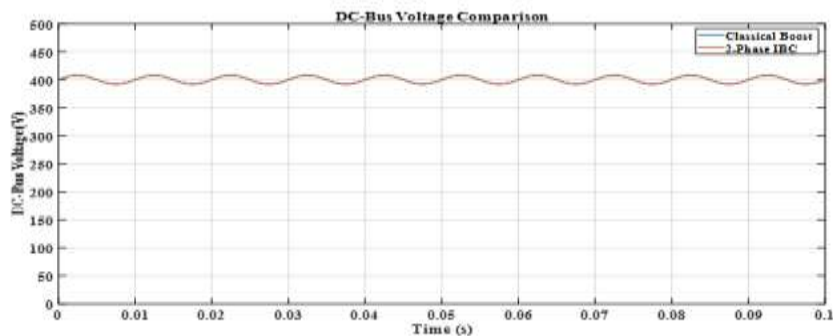


Fig. 4: DC-Bus Voltage waveform

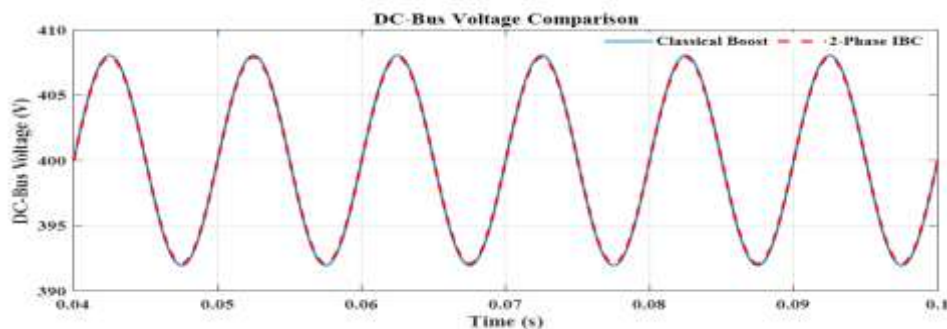


Fig. 5: Zoomed version of DC-Bus Voltage Comparison of Classical Boost and 2-Phase IBC.

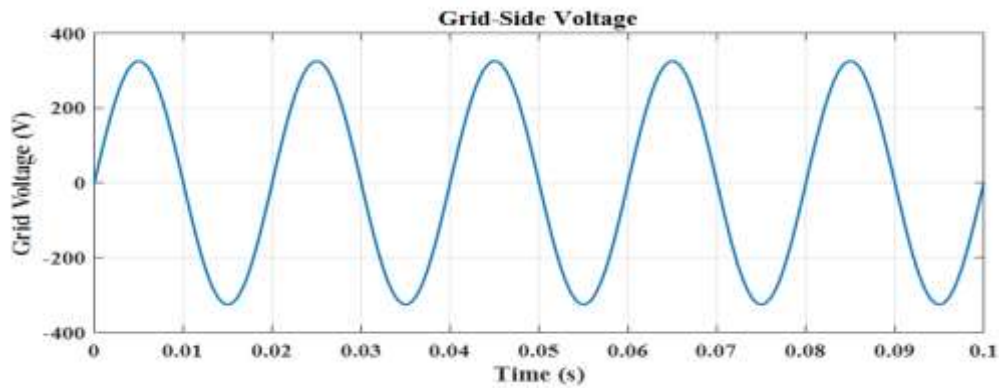


Fig. 6: Single phase Grid-injected sinusoidal Voltage waveform.

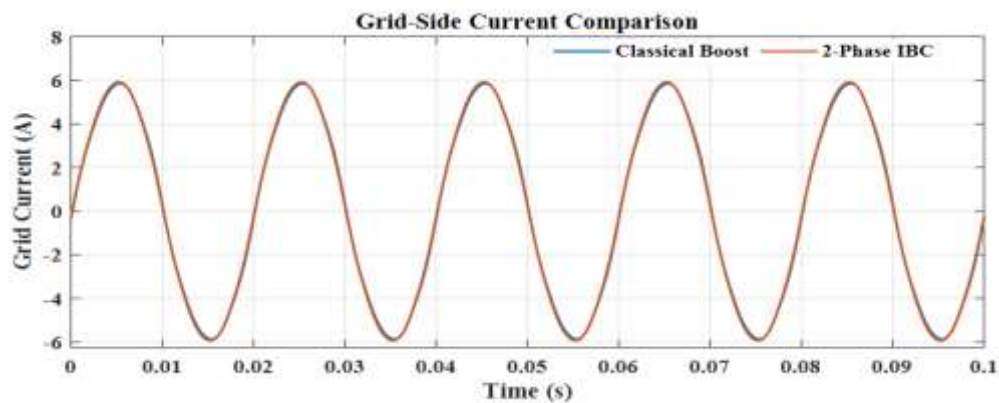


Fig. 7: Grid-Side Current Comparison of Classical Boost and 2-Phase Interleaved Boost Converters.

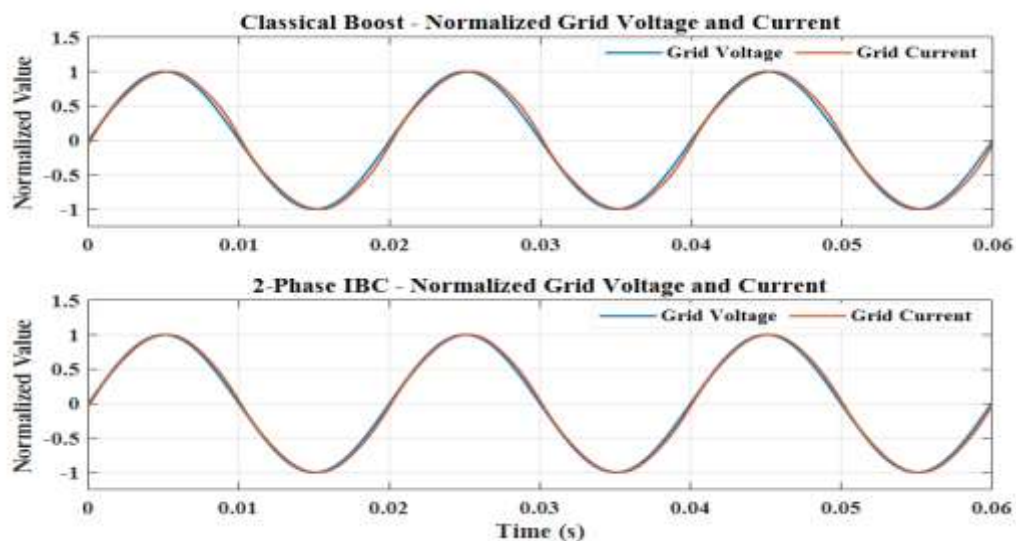


Fig. 8: Comparison of Normalized Grid Voltage and Current for Classical Boost and 2-Phase Interleaved Boost Converters showing UPF operation

5.2 Current Ripple and MPPT Stability

The classical boost incurs a 2.66 A peak-to-peak ripple around the nominal 10 A operating point shown in Fig.9. This continuous perturbation shifts the operating point across the knee of the P-V curve, introducing an intrinsic 1.25% tracking loss. In the IBC, phase interleaving attenuates the composite ripple to 0.74 A at 100 kHz, stabilizing the operating point and raising dynamic MPPT tracking efficiency above 99.5%.

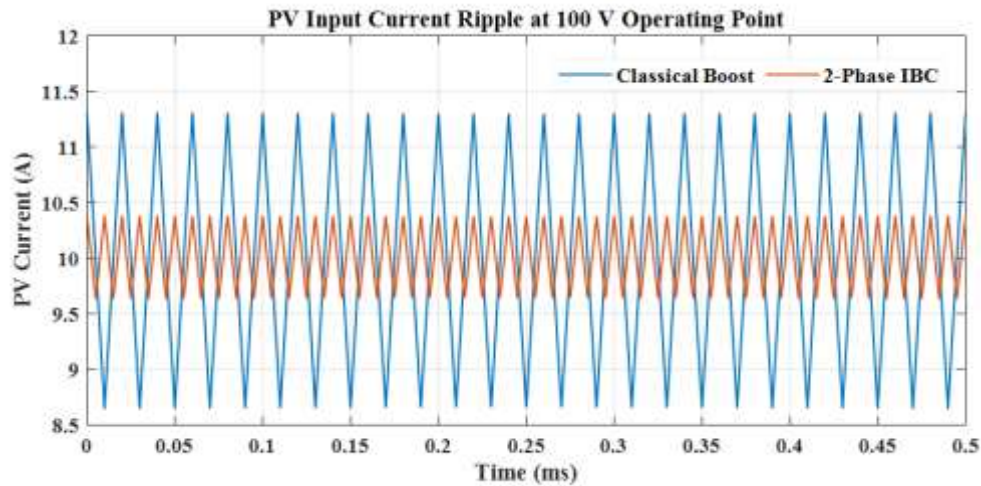


Fig. 9: PV input current ripple for both Classical and IBC.

5.3 Loss Distribution

The classical boost dissipates 19.37 W at full load (98.06% efficiency). Conduction loss in switch Q is 6.00 W. In the IBC, total stage losses drop to 12.12 W, raising efficiency to 98.79% shown in Fig.10 & Fig.11. Halving the leg currents cuts active switch conduction loss to 3.01 W, while inductor copper loss falls from 5.02 W to 1.54 W.

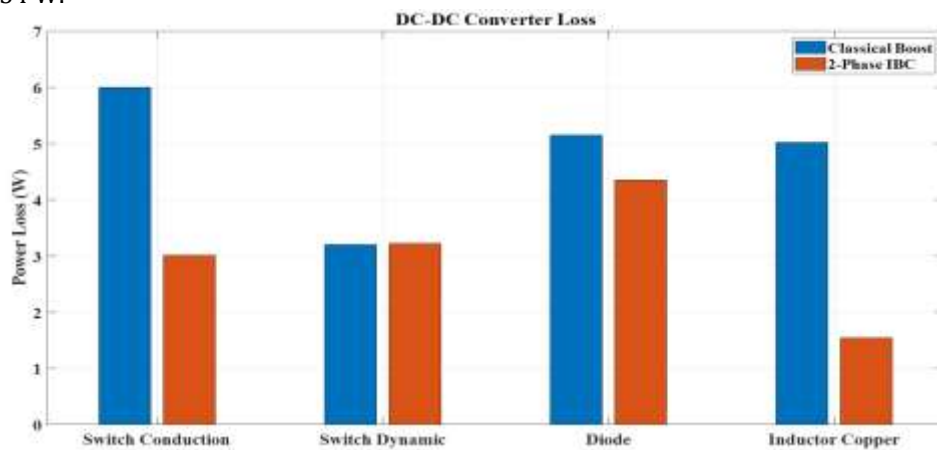


Fig.10. Power loss comparison of the classical boost converter and 2-phase IBC.

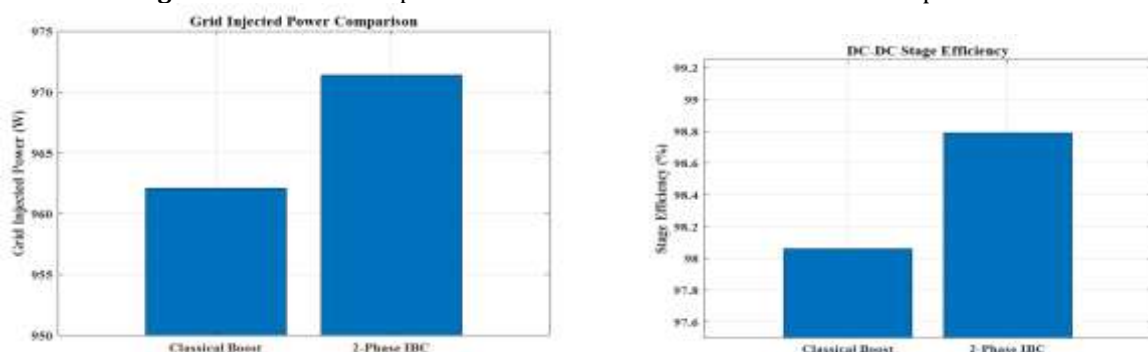


Fig.11: (a) Grid Injected Power comparison (b). Efficiencies of the classical boost converter and 2-phase IBC.

5.4 Grid Harmonic Spectra

Under PR control, the grid currents in Fig.12&13 aligns with the utility voltage at 0.999 power factor. Fast Fourier Transform (FFT) analysis shows Fig.14 &15 that while both topologies satisfy the IEEE 1547-2018 limit of THD < 5.0%, the IBC system achieves 1.62% THD compared to 2.84% in the classical setup. This difference arises because reduced DC-bus high-frequency ripple suppresses sideband modulation intermodulation inside the inverter bridge.

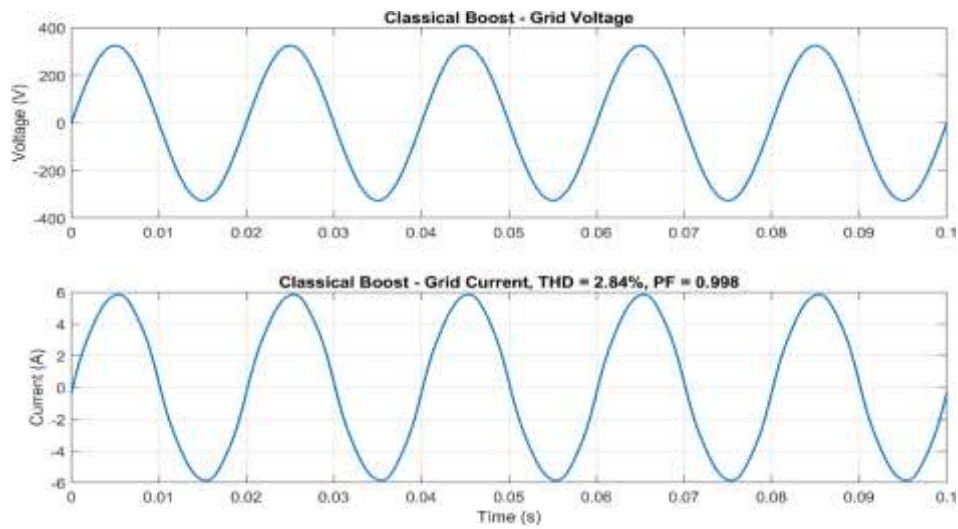


Fig.12: Grid-Side Voltage and Current Waveforms of the classical Boost Converter

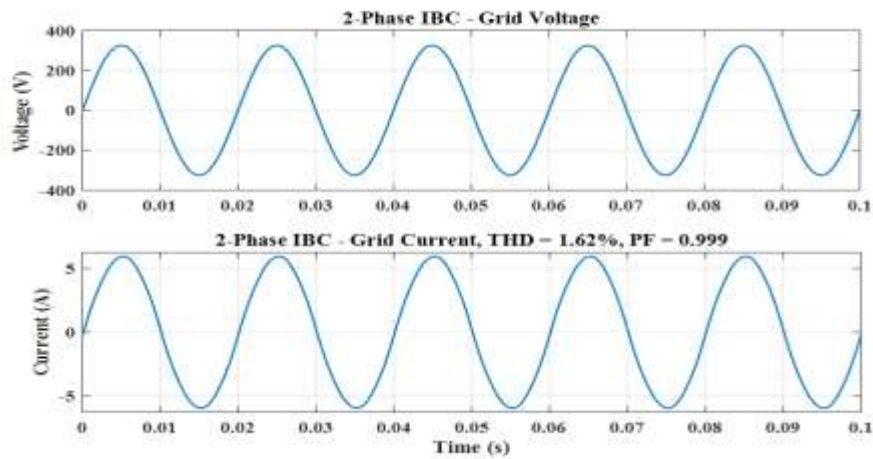


Fig. 13: Grid-Side Voltage and Current Waveforms of the 2-Phase Interleaved Boost Converter

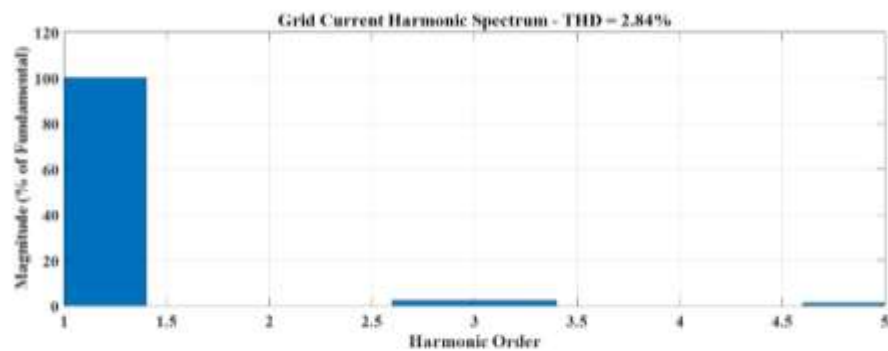


Fig.14: Harmonic spectra of classical Boost Converter

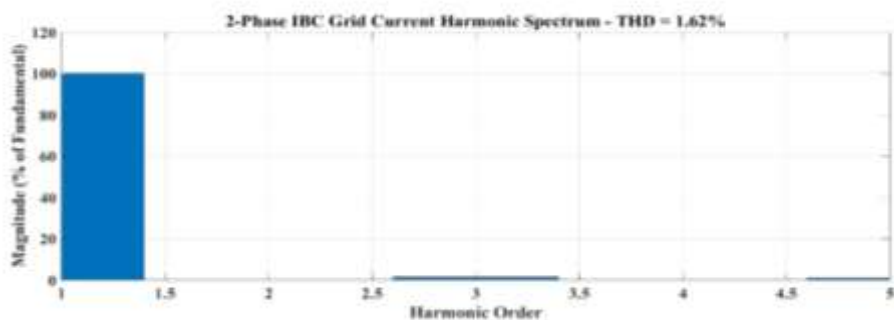


Fig.-15: Harmonic spectra of 2-Phase Interleaved Boost Converter

Table 3: Measured Converter Characteristics at 1 kW Rated Output

Measured Parameter	Classical Boost	2-Phase IBC
Operating PV Voltage V_{pv}	100V	100.0 V
Operating PV Current I_{pv}	9.98 A	10.01 A
PV Current Ripple ΔI_{pv}	2.66 A (26.67%)	0.74 A (7.42%)
Effective Ripple Frequency	50 kHz	100 kHz
Switch Conduction Dissipation	6.00 W	3.01 W
Switch Dynamic Dissipation	3.20 W	3.22 W
Diode Conduction and Dynamic	5.15 W	4.35 W
Inductor Copper Loss	5.02 W	1.54 W
Combined DC-DC Losses	19.37 W	12.12 W
Stage Efficiency	98.06%	98.79%
Cdc High-Frequency RMS Current	4.33 A	2.50 A
DC Bus 100 Hz Voltage Ripple	16.10 V	15.82 V
Grid Injected Power P_{grid}	962.1 W	971.4 W
Grid Injected Current THD	2.84%	1.62%
Power Factor	0.998	0.999

6. CONCLUSION

This study evaluated classical and 2-phase interleaved boost converters in a 1 kW, 100 V PV to 230 V single-phase grid conversion setup. The principal results indicate, Interleaving suppresses PV array current ripple by 72.2% (from 2.66 A to 0.74 A), doubling the effective switching frequency to 100 kHz and eliminating steady-state MPPT tracking oscillations. Active switch conduction losses are cut by 49.8% (from 6.00 W to 3.01 W). Total front-end losses decrease from 19.37 W to 12.12 W, raising DC-DC conversion efficiency to 98.79%. High-frequency RMS current through the intermediate bus capacitor decreases by 42.3% (from 4.33 A to 2.50 A), which extends capacitor operating life and supports the use of compact film capacitors. Single-phase power flow is responsible for maintaining the inherent 100 Hz voltage ripple, and the IBC is responsible for mitigating high-frequency modulation cross-coupling. This results in a reduction in grid current total harmonic distortion (THD) from 2.84% to 1.62%.

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