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Comparative Analysis of Buck and Push-Pull DC-DC Converter

Kiran Bhosle
Student Member, IEEE
Department of Electrical Engineering
S.G.S.I.T.S.
Indore, Madhya Pradesh, India

R. S. Mandloi
Senior Member, IEEE
Department of Electrical Engineering
S.G.S.I.T.S.
Indore, Madhya Pradesh, India

Abstract - **This study examines the performance of two basic DC-DC converter topologies: the isolated push-pull converter and the non-isolated buck converter, using MATLAB/Simulink simulations. Converters are compared in terms of output voltage, voltage and current ripple, total harmonic distortion (THD) and efficiency using matched design parameters. According to the results, the push-pull converter achieves near-zero THD and superior harmonic performance at the expense of higher voltage drop and poorer efficiency, while the buck converter offers better output voltage regulation and simplicity. This thorough comparison provides detailed recommendations for choosing DC–DC converter topologies in real-world power electronics applications, backed by waveform and frequency-domain studies.**

Keywords - **Buck converter, Push-Pull converter, THD, Efficiency.**

I. INTRODUCTION

DC-DC converters are key components in the development of many critical applications. In renewable energy systems, they are widely used to connect energy generation sources to energy storage systems or the utility grid. For example, solar photovoltaic (PV) arrays use DC-DC converters not only to optimize power extraction using Maximum Power Point Tracking (MPPT) but also to convert it into stable, grid-compatible DC voltages [1][2][3]. Electric vehicles and hybrid electric vehicles heavily depend on these devices for managing power flow between battery packs, electric motors, and auxiliary systems where high voltage gain is needed along with robust control strategies [4]. In embedded applications as well as microcontrollers, DC-DC converters downstep higher battery voltages to lower operating voltages that sensitive digital circuitry requires for the integrity of power and an increase in battery life [5][6]. Their use is not limited to this; they find use in telecommunication, battery charging systems, and other safety-critical systems too [7][8].

DC-DC converter topologies are generally divided into two categories: non-isolated and isolated converters. This division is based on whether or not there exists a galvanic isolation barrier (usually a transformer) between the input and output stages . It is very important to compare both these topologies since each class has its own specific advantages that make them appropriate for different application requirements. Such an extensive evaluation under standardized conditions will be very useful for design engineers in accurately choosing between safety, efficiency, size, cost, and performance optimizations [9].

Non-isolated DC-DC converters have a direct electrical connection between input and output; therefore, they are usually simpler, more compact, and more efficient since there is no transformer [10]. The topologies most commonly used for non-isolated converters are Buck (step-down), Boost (step-up), and Buck-Boost (step-up/step-down) converters [11]. The application of the Buck converter falls under those that require a lower output voltage. An example is point-of-load regulation for microcontrollers .

On the other hand, isolated DC-DC converters utilize a transformer to provide galvanic isolation. This is essential for safety by protecting the user and sensitive loads from dangerous voltages and reducing noise through the prevention of common-mode noise propagation. Standard isolated topologies are the Forward, Flyback, and Push-Pull converters. Push-Pull converters are applicable for higher power with better transformer utilization and efficiency in servers and safety-critical telecom infrastructure .

Several important parameters are used to assess the performance of DC-DC converters. Efficiency is the most important one because it measures how well power is converted and affects heat generation[12][13]. Voltage gain is the ratio of output to input voltage and indicates whether a converter steps up or down voltage[14]. Output ripples in voltage and current should be as small as possible for stable operation of loads and longer life of the power source[15][16] Transient response indicates how good a converter is at keeping an output stable when there are sudden changes in load or input, which matters a lot for dynamic applications[17][18]. Lastly, control complexity refers to the detail in the control circuitry and algorithms, which has an impact on total cost and reliability.

Although there has been a lot of research on different types of DC-DC converters, a major gap in research still exists regarding a direct, systematic, and unified comparison of the performance of both isolated and non-isolated converters under the same

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operating conditions. This is highlighted in literature sources. Most existing studies concentrate on particular topologies or do comparative studies between converters belonging to the same class. Very few provide an overall comparison that cuts across the isolated/non-isolated divide as seen in references [19][20]. The absence of such a unified comparative study makes it difficult for designers to arrive at well-informed decisions.

This work will attempt to fill this gap by performing a fair and systematic performance comparison of some selected non-isolated (Buck) and isolated (Push-Pull) DC-DC converter topologies. The main aim is to create an integrated framework for their operational characteristics and trade-offs. The evaluation will be carried out thoroughly through MATLAB/Simulink simulations, enabling a controlled testing environment and accurate measurement of the above-mentioned performance parameters. The knowledge gained from such a comparison would help in understanding better the merits and demerits of each type of converter toward making more informed design decisions in developing robust and efficient power electronic systems.

II. DC-DC CONVERTER TOPOLOGY

A. Non-Isolated Converter Topologies

Non-isolated converter (directly connect input and output sharing ground, transferring energy through switches without transformers. They offer excellent efficiency, simplicity, and minimal cost but provide no electrical separation. Used in CPU power supplies and battery chargers where isolation isn't essential.

1) Buck Converter

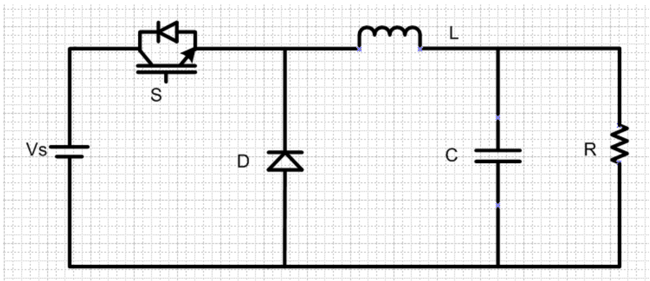

Fig. 1. Buck Converter

The buck converter operates through a two-phase switching cycle that transforms higher input voltage to lower output voltage. During the switch-on phase, the MOSFET conducts and creates a direct path from the input voltage through the switch to the inductor and load. In this state, the inductor voltage equals the difference between input and output voltage ($V_L = V_{in} - V_{out}$), leading the inductor current to rise linearly . The capacitor charges as the inductor current increases the load current, storing energy for later use. When the switch turns off, the freewheeling diode conducts automatically to maintain current continuity through the inductor, producing a discharge channel where current flows from the inductor through the diode back to the output capacitor and load. The inductor voltage turns negative ($V_L = -V_{out}$) during this off-phase, which results in a linear drop in the inductor current. The basic voltage conversion relation

$$V_{out} = D \cdot V_{in} \tag{1}$$

where V_{out} is output voltage, V_{in} is input voltage, D is the duty cycle, results from steady-state operation, where the average inductor voltage must be zero for a whole switching cycle. The inductor value can be computed based on the desired current ripple using the formula

$$L = \frac{V_{out} \times (V_{in} - V_{out})}{\Delta I_L \times f_s \times V_{in}} \tag{2}$$

In this equation, fs represents the switching frequency while ΔI_L indicates the peak-to-peak inductor current ripple. Lastly, capacitor sizing will affect output voltage ripple; it can roughly be estimated by

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{out}} \tag{3}$$

with ΔV_{out} being the acceptable peak-to-peak output voltage ripple. The inductor current displays a peak-to-peak amplitude triangle ripple pattern. Although the buck converter does not offer galvanic isolation between input and output circuits, its simplicity, direct energy transfer path, and lack of transformer losses make it extremely efficient.

B. Isolated Converter Topologies

Transformers are used by isolated converters to transmit energy magnetically, totally isolating the input and output circuits. They offer safety isolation, eliminate ground loops, and block noise, but they are more complex and result in transformer losses. utilized in industrial systems that need electrical separation, communications, and medical equipment

1) Push-Pull Converter

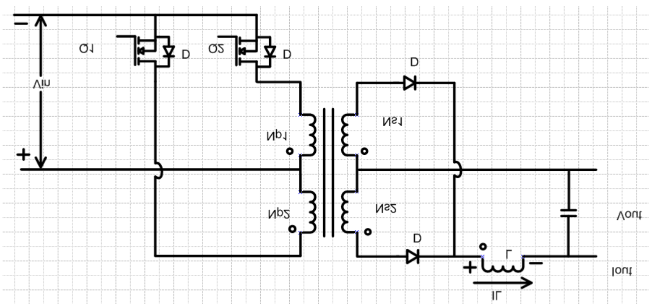

Fig. 2. Push-Pull Converter

The push-pull converter uses a transformer and two complimentary switches to accomplish isolated voltage conversion via a bidirectional energy transfer mechanism.

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Current can pass through the upper half of the center-tapped transformer primary winding during the first half of the switching cycle when switch Q1 is turned on and switch Q2 is left off. As a result, the transformer core experiences a positive magnetic flux, which causes the secondary winding to experience a matching voltage that forward-biases the first rectifier diode (D1). When D1 is conducting, current increases linearly through the output inductor.

In this case, the off-state switch Q2 has a voltage stress of about 2·Vin because the transformer is center-tapped. In the second part of the switching cycle, when Q1 turns off and Q2 turns on, it forces current through the bottom half of the primary winding. This makes the magnetic flux reverse direction (negative flux) and induces a voltage of opposite polarity in the secondary that forward-biases D2, the second rectifier diode. The output inductor current continues to flow through D2 with an identical rate of change. Such symmetric alternating switch operation allows bidirectional core utilization to be much more efficient than single-ended transformer operation.

Full-wave rectification by the push-pull gives energy transfer pulses at 2·fs, which means lower output voltage ripple for the same size capacitor compared to buck converters. In steady-state operation with a symmetric duty cycle, there will be no flux imbalance and therefore no saturation; thus, we can write the relation for output voltage as

$$V_{out} = V_{in} \times D \times 2 \times \frac{N_s}{N_p} \tag{4}$$

where V_{out} is output voltage, V_{in} is input voltage, D is duty cycle, N_s is number of turns on the secondary winding, N_p is number of turns on the primary winding. The output inductor is sized for ripple similar to buck:

$$L = \frac{V_{in} \times D \times T}{2 \times \Delta I_L} \tag{5}$$

The output capacitor for desired voltage ripple is

$$C = \frac{(1 - 2D) \times V}{32 \times V_{in} \times L \times f^2} \tag{6}$$

These formulas are used in selecting D, L and C such that both converter types have regulated output, stable operation, and suitable ripple performance.

The main benefits of using this topology are full galvanic isolation for safety and noise immunity, good harmonic performance, and voltage transformation that is easily adjusted by selecting an appropriate turns ratio. However, these come with increased complexity and higher switch voltage stress. Also, efficiency is generally lower than that of non-isolated topologies due to losses in the transformer core and copper plus an extra drop across the rectifier diodes.

III. DESIGN AND ANALYSIS

A. Design Specifications

Both converters were designed and simulated using the parameters that were matched as listed below to ensure methodological symmetry:

Table I. Parameters

Parameter	**Symbol**	**Buck Converter**	**Push-Pull Converter**
Input Voltage	V_{in}	12V	12V
Switching Period	T_s	$10\mu s$	$10\mu s$
Switching Frequency	f_s	100kHz	100kHz
Duty Cycle	D	50%	50%
Inductor	L	$1000\mu H$	$1000\mu H$
Output Capacitance	C	$50\mu F$	$50\mu F$
Load Resistance	R	10Ω	10Ω
Transformer Ratio	n	-	2:1

B. Simulation Framework

All simulations were done in MATLAB/Simulink R2023a using SimPowerSystems built-in blocks for switches, passive components, sources and measurement probes. The buck converter topology was modeled with a PWM generator block (set at 50% duty) followed by a MOSFET, an inductor then a freewheeling Schottky diode and finally an output LC filter. In the case of the push-pull converter, two complementary PWM signals with interlocked dead-times controlled two MOSFET switches that energized a center tapped transformer primary; on the secondary side there were two diodes used to achieve full wave rectification along with an LC output filter. Both circuits had voltage/current measurement blocks at critical nodes and FFT analysis was done through the Powergui FFT Analysis tool.

The simulation times were long enough to span many switching cycles to reach steady state, with small integration timesteps for good quality waveforms. Open-loop (fixed duty) control was used in order to isolate any effect of topology per se. Other settings were:

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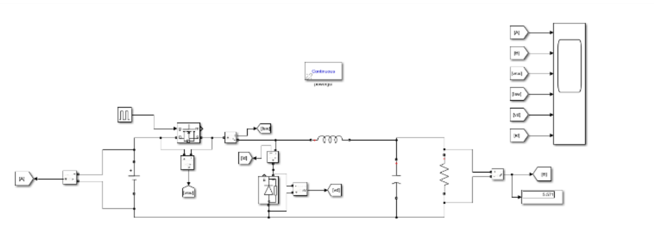

Fig. 3. Buck converter simulation circuit diagram

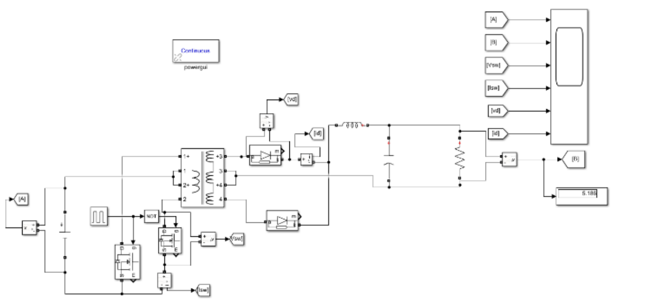

Fig. 4. Push-Pull converter simulation circuit diagram

C. Performance Metrices

The converters comparative metrics and their computational frameworks were as follows:

Output voltage V_{out}: Averaged over steady-state simulation periods.

Voltage ripple (ΔV_{out}): Calculate as peak-to-peak value in the steady-state output waveform, percentage estimated as:

$$Voltage\ Ripple(\%) = \frac{\Delta V_{out(pp)}}{V_{out(av)}} \times 100 \quad (7)$$

Current ripple(ΔI_L): For the buckinductor or push-pull output inductor.

THD: Determined using FFT(Powergui), computed as:

$$THD(\%) = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100 \quad (8)$$

Where V_n is the nth harmonic, V_1 is the fundamental.

Efficiency (η):Estimated from measured input/output voltages and average currents.

$$\eta = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}} \times 100 \quad (9)$$

Power Factor(PF): In DC-DC converter systems PF is influenced by harmonic distortion:

$$PF = \frac{1}{\sqrt{1 + THD_1^2}} \quad (10)$$

Where THD_1 denotes input current harmonic content; ideal DC-DC operation yields unity PF, but ripple and switching can lower it.

D. Control Techniques

Both converters were driven in open-loop pulse-width modulation (PWM) with a 50% duty cycle and 100kHz frequency for high consistency. The single PWM signal of the buck converter switched the MOSFET, whereas the push-pull converter required two phase-shifted complementary PWM signals applied to the primary side pair of switches with appropriate dead-times for shoot-through protection. No feedback or closed-loop regulation was used to ensure that any differences in performance would be due to the steady-state inherent characteristics of each topology.

IV. RESULTS AND DISCUSSION

In this part, simulated results are presented along with waveform analysis and important performance observations. Figures and tables are used here as placeholders that will be illustrated later and with more details.

A. Buck Converter Results

The buck converter produced a steady-state output voltage (V_{out}) of 5.57 V, compared to a theoretical value of 6.0 V for D=0.5 and V_{in}=12 V (see Fig. 3.a). This results in an error of 7.17%, which can be attributed to all types of losses: switching loss, diode loss, inductor DCR loss, and output capacitor ESR loss. The output waveform displayed some periodic ripple on top of the DC level with peak-to-peak ripple and small overshoot at switch transitions.

For the selected L, C, and load R, the inductor current displayed a distinctive triangle waveform with ripple that matched analytical calculations (see Fig. 3.c and Fig. 3.e).

With dominant energy at the switching frequency (100 kHz) and harmonics at multiples thereof, FFT analysis revealed a considerable harmonic presence, yielding THD of 3.44%.

Circuit dynamics caused switch voltage to peak slightly over Vin during off-state, confirming the need for suitable voltage ratings (see Fig. 3.b). The waveforms of the switch and diode current were complimentary, indicating that the operation sequence was accurate (see Fig. 3.d).

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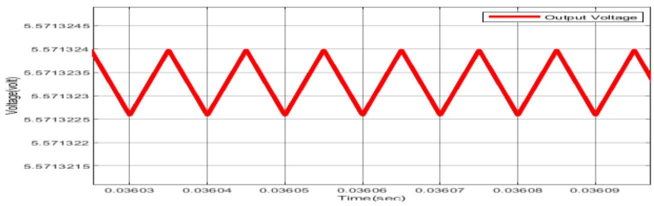

Fig. 3.a. Output voltage

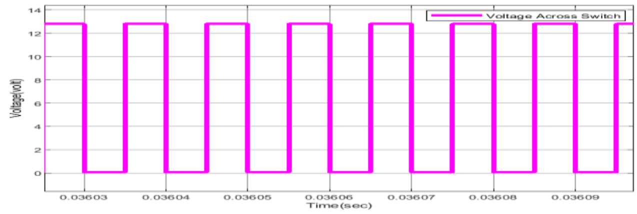

Fig. 3.b. Voltage across switch

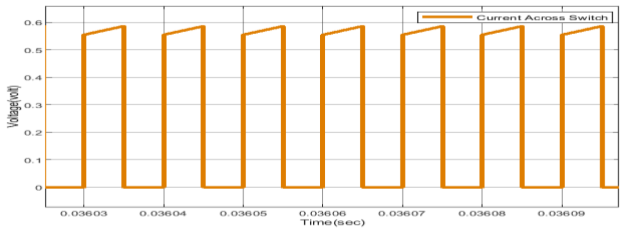

Fig. 3.c. Current across switch

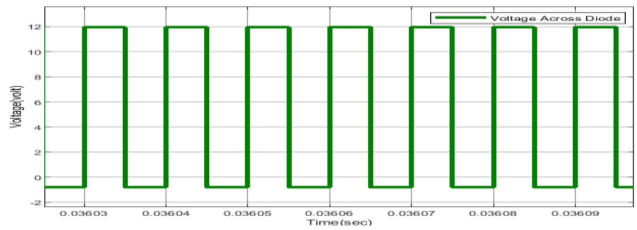

Fig. 3.d. Voltage across diode

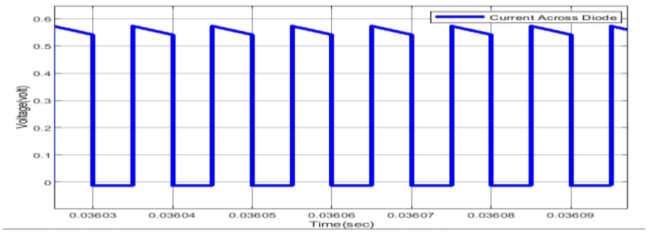

Fig. 3.e. Current across diode

B. Push-Pull Converter Results

The push-pull showed an output voltage of 5.18 V compared to a theoretical value of 6.0 V (V_{in}=12 V, D=0.5, n=2:1) (see Fig. 4.a). The larger error of 13.67% is due to transformer losses (copper core, leakage), path complexity, and semiconductor drops from full-wave secondary rectification. Output voltage ripple was slightly less than that in the buck case because it benefited from a doubled effective output frequency (200 kHz full-wave rectification) and transformer filtering so that the same output capacitor could more easily filter this higher frequency ripple. FFT spectrum analysis showed negligible harmonics—a THD of 0.00%. This reflects the superior harmonic attenuation by push-pull transformer isolation, full-wave action, and better inherent EMI performance (see Fig. 4.b, Fig. 4.c, Fig. 4.d and Fig. 4.e).

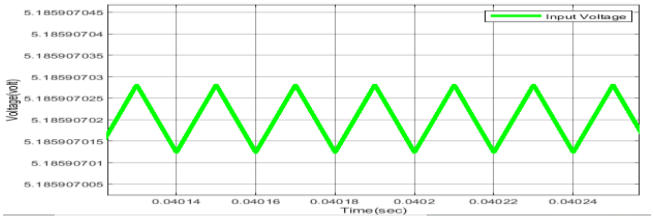

Fig. 4.a. Output voltage

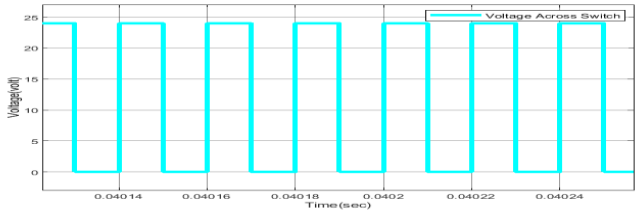

Fig. 4.b. Voltage across switch

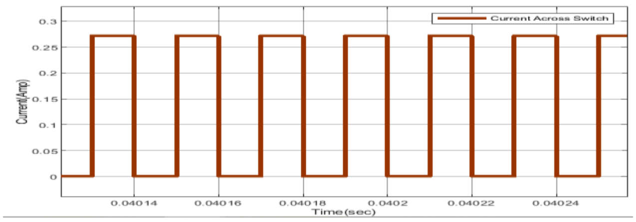

Fig. 4.c. Current across switch

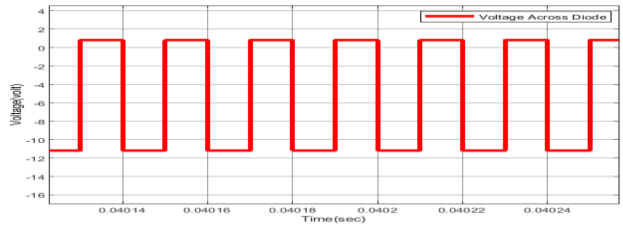

Fig. 4.d. Voltage across diode

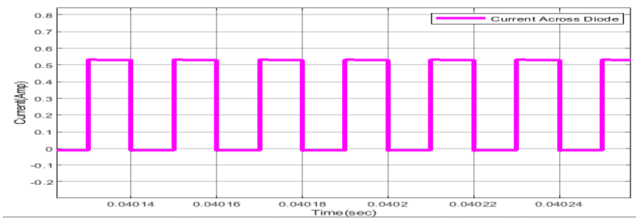

Fig. 4.e. Current across diode

C. Waveform and Metric Comparisons

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Output Voltage Quality: The push-pull displayed a little lower voltage, a bigger error, and nearly zero THD, whereas the buck demonstrated better voltage regulation (smaller error from theoretical) but higher THD.

Voltage/Current Ripple: Better ripple attenuation with equal component values was made possible by the push-pull's greater output ripple frequency.

Switching Stresses: The buck voltage stress was almost doubled for the push-pull switches, which had an impact on losses, cost, and selection.

Component Complexity: The push-pull required two switches, one transformer, two secondary-side diodes, and the output filter, adding complexity and BOM cost, but the buck converter had a simpler design with just one switch, one diode, one inductor, and one capacitor.

When compared to the buck topology, switch voltage stress reached roughly twice Vin (around 25 V), highlighting the need for higher-rated primary switches.

II. Simulation Data Table

Metric	**Buck Converter**	**Push-Pull Converter**
V_{out} (measured)	5.57V	5.18V
Theoretical V_{out}	6.00V	6.00V
Voltage Error (%)	7.17%	13.67%
THD (%)	3.44	0.00
Fundamental Frequency	100 kHz	100 kHz
Output Ripple (rel.)	Higher	Lower
Component Count	Lower	Higher
Isolation	No	Isolated
Efficiency	High	Moderate

V. COMPARITIVE ANALYSIS

This section summarizes all simulation results, frame-by-frame, for critical design and application trade-offs. Where each topology has an advantage over others is highlighted in comparative tables and graphs (placeholders).

Output Voltage and Regulation: Buck converter gives better output regulation with lower voltage drop for any set of non-idealities. Direct connection with fewer voltage drops reduces the loss at the output.

THD: Push-pull gives much improved THD (<0.01%) because of transformer isolation and full-wave topology. For designs that are sensitive to power quality, push-pull is the best option.

Efficiency: Buck converter keeps higher efficiency empirically and in literature for single-output step-down applications without isolation; push-pull has losses from the transformer, an extra diode, and more switch loss.

Power Factor: Both topologies will have a power factor near unity when used with purely resistive load and under DC operation; however, buck may show slightly higher PF due to lower input distortion.

Component and Design Complexity: Buck converters are more economical and simpler to design in low-power, non-isolated use cases. Push-pull converters need transformer design, flux balancing, high-voltage MOSFETs snubber/EMI management.

Voltage and Current Ripple: The output of push-pull enjoys the benefit of high-frequency ripple; hence filtering capability is better for any given set of components.

Table III. Comparision of Buck and Push-Pull Converter

Feature	**Buck Advantage**	**Push-Pull Advantage**
Simplicity	High	Low
Output THD	Low	High
Regulation	Best	Acceptable
Isolation	No	Yes
Component Cost	Lower	Higher
Flexibility	Less	Multi-output, scalable
EMI/Noise	Moderate	Low

VI. CONCLUSION

This deep study, based on tough simulation and standard metric evaluation, shows that the buck converter is the best choice for cases where efficiency, simplicity, and low voltage drop matter most in non-isolated settings. On the other hand, the push-pull converter is best known for having zero output THD, transformer isolation, output flexibility, and better noise protection even if it comes with lower voltage control, complexity, and efficiency. The choice between these converters should be based on what the specific application needs: use the buck in cost- and efficiency-sensitive cases with local loads and use the push-pull when galvanic isolation or ultra-low harmonics or multi-rail requirements are needed.

Future work should include hardware validation, closed-loop control comparisons, and scaling to variable input/output power ranges. Analyzing the effects of temperature variations, different transformer turns ratios, and employing soft-switching or synchronous rectification will also help understand practical limitations better.

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