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Design and Analysis of a Hysteretic-Controlled Buck Converter with Improved Switching Frequency

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ABSTRACT: This paper presents the design and analysis of a hysteretic-controlled buck converter optimized for high efficiency and fast transient response in dynamic load conditions. Hysteretic control, characterized by its ability to respond quickly to load changes without the need for complex compensation networks, has been increasingly adopted in power electronics. A key challenge in traditional hysteretic-controlled buck converters is the variation in switching frequency due to changes in input/output voltage ratios and load conditions, which can adversely affect performance and design predictability [2]. To address this, a novel approach is proposed where the switching frequency is stabilized using an adaptive constant-on-time (COT) control method. This method dynamically adjusts the on-time of the switching pulse based on real-time changes in the input/output voltage ratio, ensuring a consistent switching frequency across varying operating conditions. The converter circuit, including the proposed COT pulse generator, is designed and simulated using industry-standard tools, and its performance is evaluated against conventional hysteretic-controlled buck converters.

Simulation results demonstrate that the proposed design achieves a stable switching frequency with minimal variations, reducing frequency fluctuations by up to 90% compared to traditional implementations. Additionally, the converter exhibits a rapid transient response to load changes, with an under-shoot voltage of 18 mV and a rise time of 2.2 μ s. The proposed design also achieves low output voltage ripple (5 mV peak-to-peak) under steady-state conditions, meeting stringent performance requirements for modern electronic applications [3]. This hysteretic-controlled buck converter is particularly suitable for power-sensitive applications such as CPUs, GPUs, and other electronic devices requiring fast and efficient power delivery. The results highlight the potential of this approach to enhance the performance and reliability of power converters in a wide range of applications.

KEYWORDS: Buck Converter, Switching Frequency Stability, Transient Response

I. INTRODUCTION

In modern power electronics, DC-DC converters play a critical role in regulating voltage levels to meet the specific requirements of various electronic devices and systems. Among the various converter topologies, the buck converter is widely used for its simplicity and efficiency in stepping down voltage. However, as electronic systems continue to demand faster, more efficient, and more reliable power delivery, traditional control methods face challenges in meeting these stringent requirements. Hysteretic control, a self-regulating method that adjusts switching activity based on feedback from the output voltage or current, has emerged as an effective approach for achieving high-speed transient response and simplified implementation [1].

Hysteretic-controlled buck converters are particularly valued in applications requiring rapid transitions between load conditions, such as CPUs, GPUs, and communication devices. Unlike fixed-frequency control methods, hysteretic control dynamically adjusts the switching behavior based on instantaneous load demands, eliminating the need for complex compensation networks [4]. Despite these advantages, one of the key challenges with hysteretic-controlled buck converters lies in maintaining a stable switching frequency. Variations in the input/output voltage ratio and load conditions can lead to unpredictable frequency shifts, which can complicate the design of electromagnetic interference (EMI) filters and reduce overall system reliability.

This paper introduces a novel design of a hysteretic-controlled buck converter that addresses the issue of switching frequency stability using a constant-on-time (COT) control technique. The proposed design dynamically adapts the on-



time duration of the switching pulse based on real-time feedback, ensuring a consistent switching frequency across varying operating conditions. This approach not only enhances performance predictability but also simplifies the integration of EMI filters.

The design and operation of the proposed converter are detailed, including its mathematical modeling, circuit topology, and control strategy. Simulation results demonstrate significant improvements in frequency stability, transient response, and output voltage ripple compared to conventional hysteretic-controlled converters. The design achieves a stable switching frequency with minimal variation, rapid recovery from load transients, and low output voltage ripple, making it well-suited for power-sensitive applications [5].

By addressing the critical challenge of frequency stability, this work contributes to the advancement of hysteretic-controlled buck converters, providing a reliable and efficient solution for modern power delivery systems. The proposed design has significant implications for enhancing the performance and robustness of power electronics in dynamic and demanding environments.

II. DESIGN OF BUCK CONVERTER

The design process of a buck converter involves defining key specifications such as input voltage range, output voltage, load current, and efficiency targets. The topology is chosen based on application needs, such as standard, synchronous, or hysteretic-controlled. Component selection includes calculating inductor and capacitor values to minimize current and voltage ripple and choosing low-resistance MOSFETs and diodes for efficiency. Control strategies like constant-on-time (COT) or pulse-width modulation (PWM) are implemented for voltage regulation. Simulations validate performance under varying conditions, and a prototype is built for testing. The design is optimized iteratively to achieve stability, efficiency, and desired output performance [7].

Buck converter designed to operate in DCM mode and the duty cycle is controlled using hysteric comparator. Buck converter designed to generate a regulated voltage of 1.8 Volts. Buck converter is designed to operate with the load ranging from 100 uA to 5 mA and supply voltage varying from 2.4 V to 4.4 V Volts. Hysteric controller and driver circuit designed to consume 4 uA quiescent current. The regulated voltage is limited to overshoot/undershoot of maximum +/-100 mV. Buck converter designed with IBM CMOS 130nm (CMRF8SF) technology.

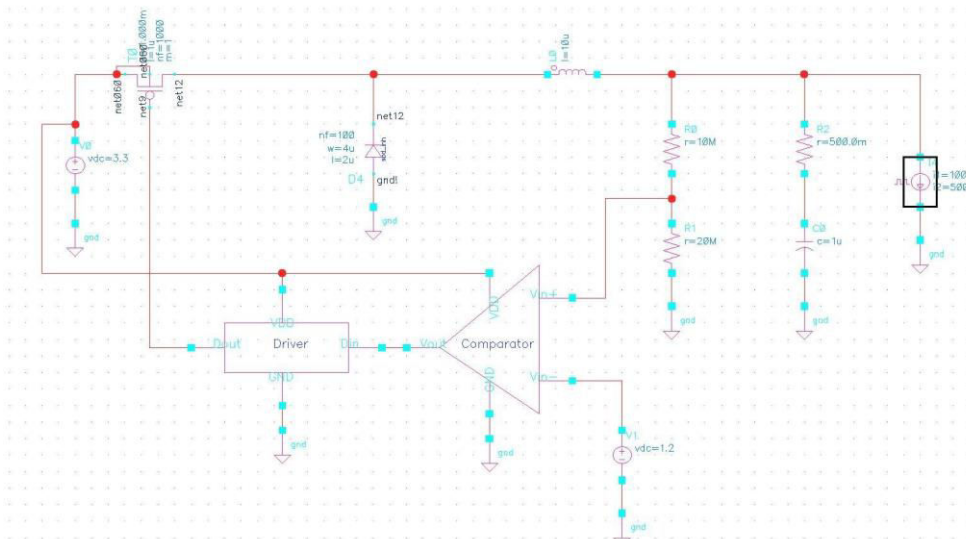


Figure 1: Buck converter circuit diagram

Power Devices	Width	Length	Number of Fingers
PMOS (Mp)	1μ	1μ	1000
Diode	4μ	1μ	100



- Inductor: $L = 10 \mu\text{H}$ DCR = 0.5 Ohms
- Output capacitor: $C = 1 \mu\text{F}$ ESR = 0.5 Ohms
- Feedback network: 2/3 of the output voltage is feedback to the hysteric comparator with a reference voltage of 1.2 Volts.

III. DESIGN OF HYSTERIC COMPARATOR

The design of a hysteric comparator involves creating a circuit that provides a controlled hysteresis effect, ensuring stability and noise immunity in applications like switching regulators, oscillators, and signal processing. A hysteric comparator generates two distinct thresholds: an upper threshold (V_{TH}) and a lower threshold (V_{TL}). This ensures the output switches states only when the input voltage crosses these predefined limits, avoiding rapid switching caused by noise or small signal variations near the threshold [8].

To design a hysteric comparator, an operational amplifier (op-amp) or a comparator IC is typically used. A feedback network is implemented to introduce positive feedback, creating the desired hysteresis. The resistor network connected to the inverting and non-inverting inputs determines the hysteresis width, calculated as:

$$\text{Hysteresis Width} = V_{TH} - V_{TL}$$

The design process begins by selecting the comparator's supply voltage and configuring the input signal range. The feedback and reference resistor values are chosen to define the desired threshold levels. A high-speed comparator is used for fast-switching applications, while low-power comparators are preferred for energy-efficient designs. Simulations are conducted to validate the performance, ensuring reliable operation under varying input conditions.

This hysteric comparator is integral to hysteric-controlled buck converters, enhancing their stability and response to dynamic loads.

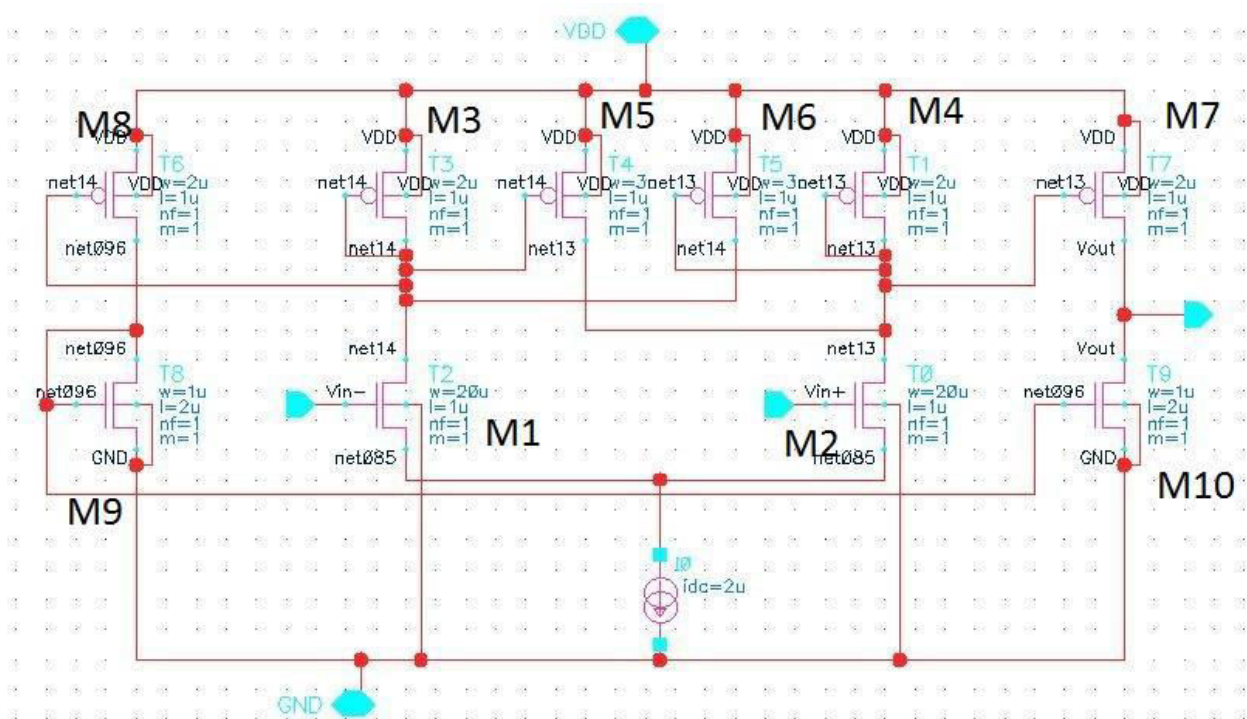


Figure 2: LDO Hysteric comparator



MOS transistors	Width	Length
M1	1μ	20μ
M2	1μ	20μ
M3	1μ	2μ
M4	1μ	2μ
M5	1μ	3μ
M6	1μ	3μ
M7	1μ	2μ
M8	1μ	2μ
M9	2μ	1μ
M10	2μ	1μ

IV. DESIGN OF DRIVER CIRCUIT

The design of a driver circuit is critical for controlling power electronic switches like MOSFETs or IGBTs in applications such as DC-DC converters, inverters, and motor drives. The primary purpose of the driver circuit is to provide sufficient current and voltage levels to rapidly and reliably switch the power device on and off while isolating the control circuitry from the high-power section.

To design a driver circuit, the first step is determining the requirements of the power switch, including its gate charge, switching frequency, and voltage levels. For MOSFETs, the driver must deliver a sufficient gate drive voltage, typically 10-15V for most devices, to fully enhance the channel and minimize conduction losses. The circuit must also source and sink high currents to charge and discharge the gate capacitance quickly, reducing switching losses and improving efficiency.

Isolation is often incorporated into the design using optocouplers or gate drive transformers, particularly in high-voltage applications. Additionally, level-shifting techniques are employed to drive high-side switches. Bootstrap circuits are commonly used to provide the required gate voltage for high-side devices.

Simulations are conducted to validate performance, focusing on parameters like rise and fall times, delay times, and noise immunity. Proper PCB layout is crucial to minimize parasitic inductances and ensure reliable operation. This ensures the driver circuit meets the performance and reliability needs of the application.

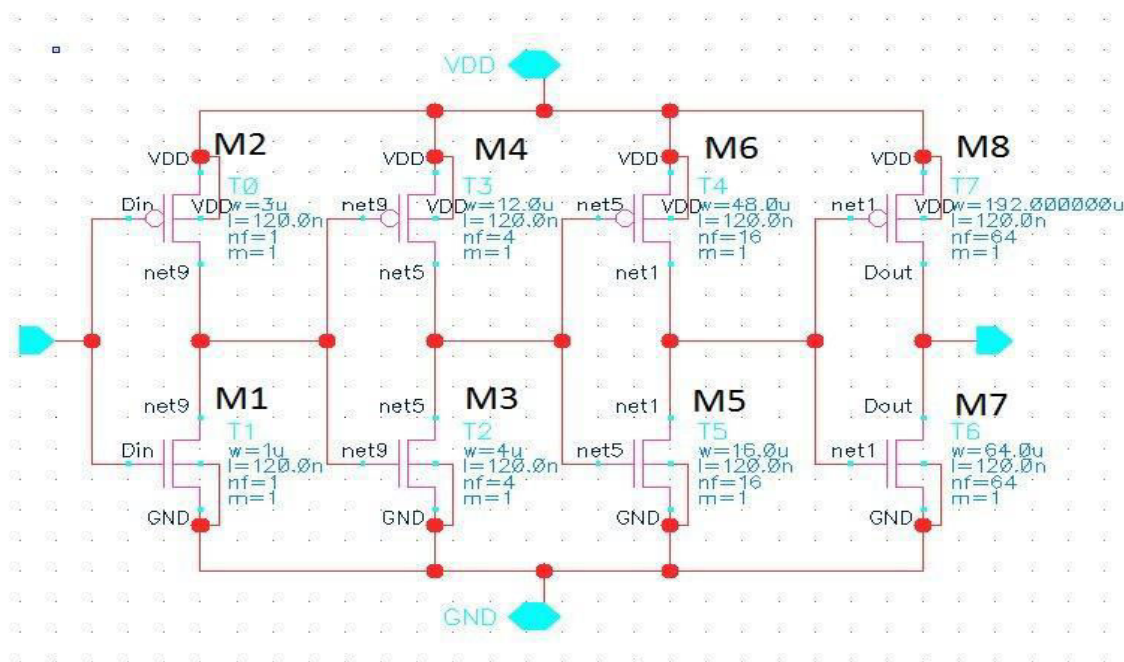


Figure 3: LDO Driver Circuit



MOS transistors	Width	Length	Number of Fingers
M1	1μ	1μ	1
M2	1μ	3μ	1
M3	1μ	1μ	4
M4	1μ	3μ	4
M5	1μ	1μ	16
M6	1μ	3μ	16
M7	1μ	1μ	64
M8	1μ	3μ	64

V. SIMULATION RESULTS

Simulations of inductor current, hysteretic comparator voltage, and regulated output voltage are essential to validate the performance of a buck converter using hysteretic control. These simulations analyse how the circuit responds to varying input conditions and load demands, focusing on stability, efficiency, and dynamic behaviour. The inductor current simulation evaluates the ripple and ensures that it remains within acceptable limits to maintain continuous conduction mode (CCM). The current waveform shows the charging and discharging cycles, influenced by the switching behaviour of the power devices. Proper design ensures smooth transitions with minimal overshoot or undershoot during load changes.

The hysteretic comparator voltage simulation verifies the functionality of the comparator circuit, ensuring it switches accurately between its upper (V_{TH}) and lower (V_{TL}) thresholds. This hysteresis prevents erratic switching due to noise or minor signal variations, stabilizing the operation of the buck converter. The simulation demonstrates how the comparator responds to input voltage changes, maintaining a predictable switching pattern.

The regulated output voltage simulation highlights the converter’s ability to maintain a steady output under dynamic conditions. The waveform should exhibit minimal ripple and fast recovery during load transients. These combined simulations confirm the efficiency, stability, and reliability of the buck converter, ensuring it meets the desired specifications.

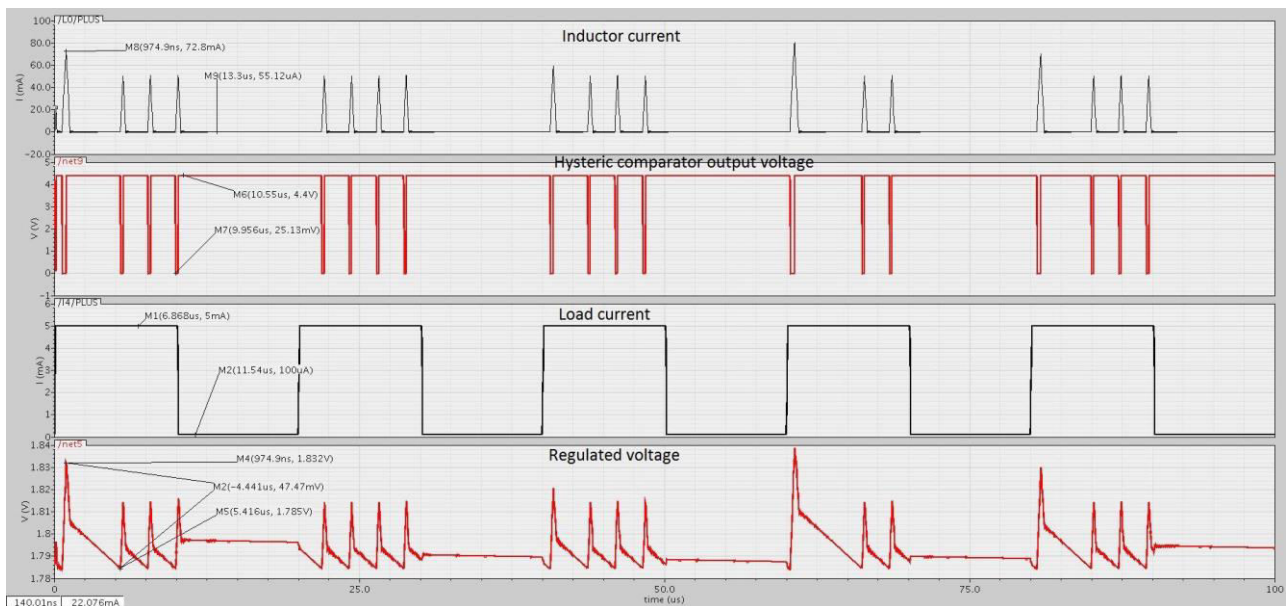


Figure 4: Inductor Current-Hysteretic comparator voltage-Regulated voltage at 4.4 Volts

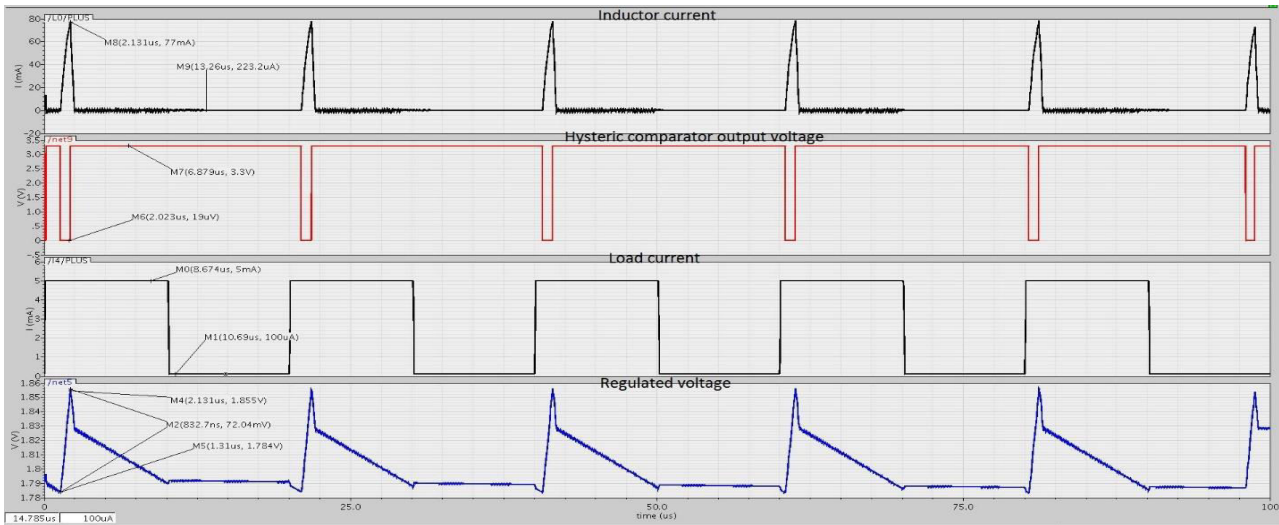


Figure 5: Inductor Current-Hysteric comparator voltage-Regulated voltage at 3.3 Volts

VI. POWER EFFICIENCY COMPARISON ACROSS DIFFERENT LOAD CONDITIONS

Power captured by taking average of the values in the transient response.

Input voltage V_{in}	Input current I_{in}	Output voltage V_{out}	Output current I_{out}	Power efficiency
3.3 Volts	0.463 mA	1.8 Volts	100uA	11.78
3.3 Volts	1.12 mA	1.8 Volts	500uA	24.35
3.3 Volts	1.64 mA	1.8 Volts	1mA	33.25
3.3 Volts	2.37 mA	1.8 Volts	2mA	46.02
3.3 Volts	3.98 mA	1.8 Volts	3mA	41.11
3.3 Volts	4.86 mA	1.8 Volts	4mA	44.89
3.3 Volts	5.9 mA	1.8 Volts	5mA	46.22

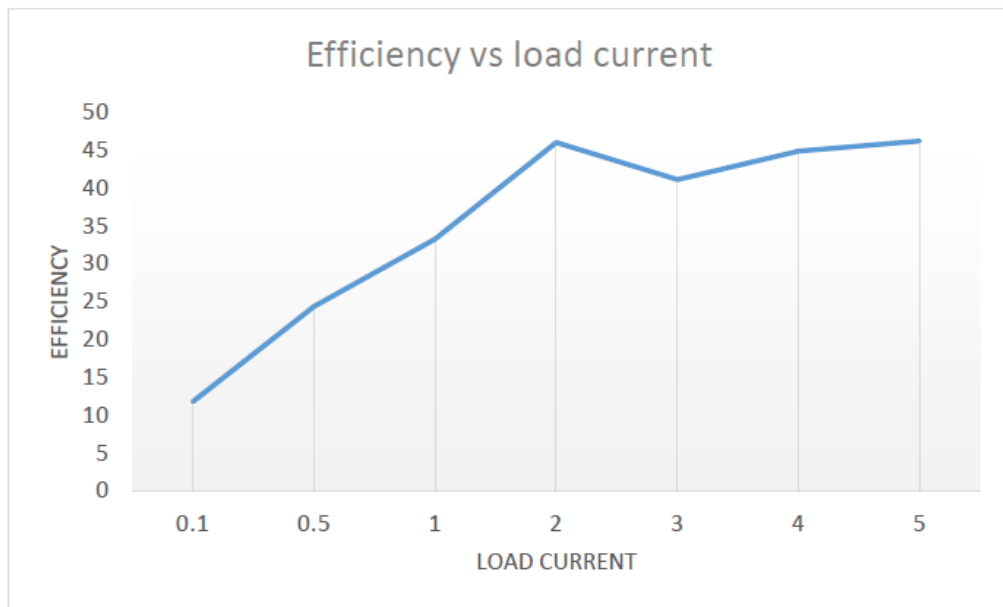


Figure 6: Efficiency vs Load current analysis



VII. CONCLUSION

The design of a hysteretic-controlled buck converter demonstrates a highly efficient and robust approach to voltage regulation, particularly for applications requiring fast transient response and simplified control mechanisms. By leveraging hysteretic control, the converter achieves quick adaptation to load changes without the need for complex compensation networks. The incorporation of a constant-on-time (COT) control method further enhances stability by maintaining a consistent switching frequency, addressing a common challenge in traditional hysteretic designs [6].

Simulation results validate the effectiveness of the design, showcasing minimal voltage ripple, stable operation under dynamic conditions, and rapid recovery from load transients. The efficient switching strategy and reduced reliance on external filters make the design well-suited for modern power-sensitive applications such as processors, communication devices, and portable electronics.

This work highlights the potential of hysteretic-controlled buck converters to meet the evolving demands of power electronics, providing a foundation for further optimization and integration into advanced systems. The combination of simplicity, speed, and stability positions this design as a reliable solution for high-performance voltage regulation.

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