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AN EVALUATION OF CURRENT MODE AND VOLTAGE MODE CONTROL TECHNIQUES FOR DC-DC CONVERTERS

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ABSTRACT: The current mode control (CMC) technology is especially promising in PV applications since the system's PV panels are intermittent. This study takes into account the voltage control mode, average current control, peak current programmed control, hysteresis current, and methods. The buck converter, a common DC-DC converter in power electronics, steps down the DC voltage from a higher level to a lower one. Current mode control (CMC) and voltage mode control (VMC) are two alternative control methods that may be used to regulate the buck converter. This article compares and contrasts the low-voltage uses of VMC and CMC. The aim is to compare the two control approaches based on their benefits and drawbacks, as well as how well they perform in terms of stability, transient responsiveness, and efficiency.

KEYWORDS: DC-DC Converter, Transient Response

1. INTRODUCTION

The power converter's fundamental working concept is to regulate the output voltage by controlling the duty cycle of a switch, often a MOSFET. The input voltage, the load resistance, and the switching frequency all influence the duty cycle, which is proportional to the output voltage [1]. Voltage mode control and current mode control are the two main control strategies for the buck converter [2][3].

In a buck converter, voltage mode control (VMC) is the traditional and often used control mechanism. In VMC, the switch's duty cycle is adjusted in response to the error signal after the output voltage is compared to a reference value. The duty cycle is altered by the controller using an amplified error signal.[2][4]
The feedback signal in the control technique known as current mode control (CMC) is inductor current. The control circuitry adjusts the switch duty cycle to maintain the required inductor current. The main advantage of CMC is its rapid transient reaction since the inductor current is instantaneous [5]. The control circuitry may quickly alter the switch duty cycle in response to changes in the load current to maintain a constant output voltage. Current mode control, sometimes known as CMC, is a more contemporary technique for controlling buck converters. The switch duty cycle is altered depending on the inductor current rather than the output voltage [8][9].

In the presented work section I, highlights a brief introduction about the current mode control and voltage mode actions. In section II, a brief literature survey has been carried out for different variations in VMC and CMC. In the section III, current control techniques has been discussed along with a brief literature survey based on the different parameters like stability, transient response, and efficiency. In the IV section a brief relative comparison hasbeen carried out based on their relative merits and limitations. Finally, a conclusion is drawn in the V section based on the thorough analysis of both the techniques.

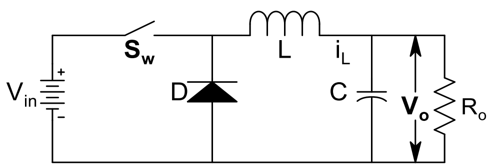


Fig.1 Diagram of Buck Converter

Nomenclature

CMC	Current Mode Control
VMC	Voltage Mode Control
AVMC	Adaptive Voltage Mode
FLC	Fuzzy Logic Control
SM	Sliding Mode
PCMC	Peak Current Mode Control
ACMC	Average Current Mode Control
HCMC	Hysteresis Current Mode Control
COTCMC	Constant On Time Current Mode Control

Section I: Voltage Mode Control

Buck converters have been using the venerable control method known as voltage mode control for many years. It compares the output voltage to a reference voltage and changes the duty cycle of the switching signal to regulate the output voltage [6][7]. There are certain limitations to voltage mode control, including [8][9][10].

1. A delayed transient response.
2. A small bandwidth, and poor stability.
3. Separate logic startup and fault prevention are required.
4. No ability to manage current.

Researchers have suggested a number of changes to voltage mode control, including adaptive voltage mode control, fuzzy logic control, sliding mode control, two loop CMC, etc. to get around these restrictions [11][12].

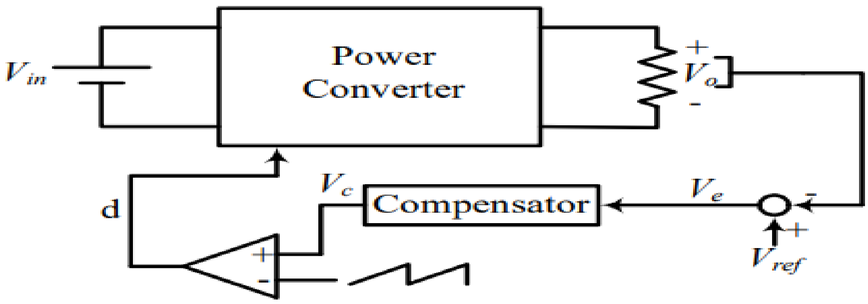


Fig.2Block Diagram of a voltage-mode controller

Current Mode Control (CMC)

It is a widely used technique for controlling the response of buck converters in terms of voltage. Because of its greater stability margins and superior transient responsiveness, it is preferable over voltage mode control (VMC) [3][5]. The buck converter is a widely used topology in power electronics, and the input voltage is stepped down to a lower output value using it. One of the main difficulties in developing a buck converter is to achieve fast transient response and good stability while maintaining a high efficiency.

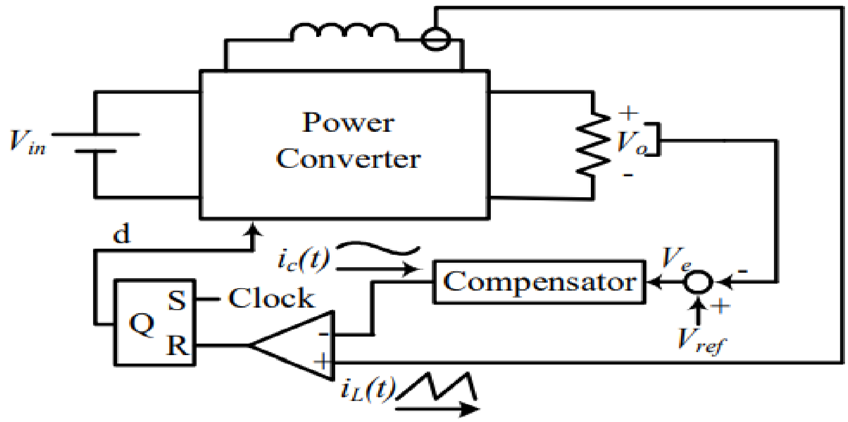


Fig 3: Block diagram of a current-mode controller

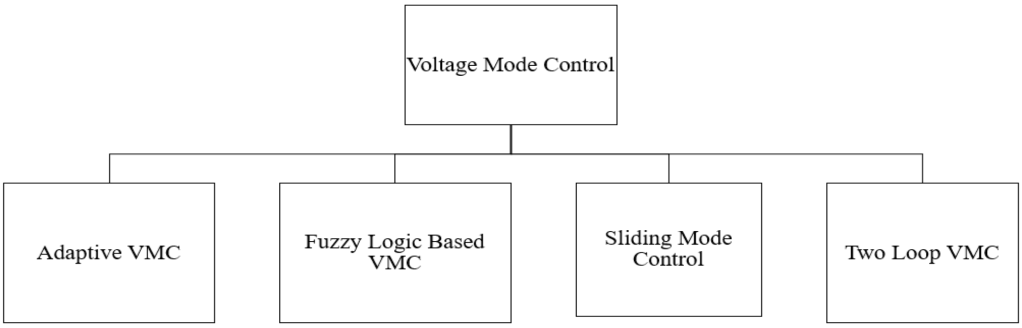
Table 1. Comparison between VMC and CMC

Characteristics	CMC	VMC
Rejection of line disturbances	Good (Inherent)	Very Good
Rejection Load disturbances	Good (Constant BW)	Good
Constant Frequency	Excellent	Excellent
Predictable EMI	Excellent	Excellent
Audible Noise suppression	Excellent	Excellent
Extreme Down Conversion	Poor	Good
Insensitivity to PCB Layout	Poor	Excellent
Excellent Stability of Loop Responses (Tolerances and long time drifts)	Excellent	Good
Simplicity of Compensation	Good	Poor
IQ (Quiescent Current)	Good	Poor
Loop Stability with use of output ceramic capacitors	Excellent	Very Good
Auto Tuning	Complex	Very Complex

Section II: Different Techniques in VMC

The Different techniques available in the literature for Voltage mode control are as follows:

Classification of VMC [6]



Adaptive Voltage Mode Control (AVMC)

It is a modification of voltage mode control that uses an adaptive gain. to adjust the control signal based on the load current and input voltage. This technique improves the transient response and stability of the converter [6][10][11][12].

Power electronic systems, in particular DC-DC converters, employ AVMC as a control approach to manage output voltage by continually adjusting the control parameters depending on system circumstances and load fluctuations [13]. By constantly modifying the control gains, AVMC's primary goal is to increase the converter's performance and resilience [8][19].

In traditional voltage mode control, fixed control gains are used to regulate the output voltage. However, these fixed gains may not provide optimal performance across different operating conditions, such as changes in load, input voltage, and component tolerances. AVMC addresses this limitation by incorporating an adaptive mechanism that continuously updates the control gains based on real-time feedback signals [9].
The adaptive mechanism in AVMC relies on the estimation of system parameters and the measurement of system variables. These parameters and variables are used to derive adaptive laws that update the control gains [14]. The estimation process can be based on various techniques such as online parameter identification algorithms, system modeling, or parameter observers.
The adaptive laws in AVMC adjust the control gains in response to changes in system parameters or operating conditions, ensuring that the control system maintains accurate and stable voltage regulation. By continuously adapting the control gains [15], AVMC can enhance the system's transient response, robustness against parameter variations, and tracking performance.
The key benefits of AVMC include [14][15]

1. Improved dynamic response to load changes
2. Enhanced stability
3. Increased efficiency over a wide range of operating conditions.

By adapting the control gains in real-time, AVMC can accommodate variations in load, input voltage, and other system parameters, resulting in better voltage regulation and system performance [16]
AVMC has been applied to various DC-DC converter topologies, including buck, boost, and buck-boost converters. The specific implementation of AVMC may vary depending on the converter topology, system requirements, and control objectives. Common techniques used in AVMC include parameter estimation, adaptive laws based on error signals, and adaptive filters to update the control gains [16][17].
Some of the researchers highlighted the different aspects of Adaptive Voltage Mode Control which are as follows
An adaptive voltage mode control method for DC-DC converters is shown in [13]. The suggested control strategy enhances the system's dynamic responsiveness and resilience by adjusting the control gains based on the load changes and operating circumstances. Results from simulations and experiments show how successful the adaptive mode voltage mode control is.[14] suggests a double-loop proportional-integral control structure for an adaptive voltage mode control strategy for buck converters. To increase dynamic responsiveness and load variation resilience, the control system adjusts the control gains depending on output voltage error and its derivative. Results from simulations and experiments attest to the effectiveness of the suggested adaptive control approach.
In [15] author highlighted an adaptive voltage mode control approach for DC-DC converters using variable control gains. The control system adjusts the control gains based on the output voltage error and its derivative, providing adaptive response to varying operating conditions and load changes. The proposed method improves system stability and robustness, as demonstrated through simulation and experimental results.[16] presents an adaptive voltage mode control strategy for DC-DC converters based on a time-varying filter. The control system adjusts the filter's parameters based on the input voltage and output voltage error, enabling adaptive response to different operating conditions and load variations. Simulation and experimental results validate the performance of the proposed adaptive control method.
In [6] author proposed a novel adaptive voltage mode control method for buck converters that uses a voltage-controlled current source and a current-controlled voltage source to generate the error signal. The adaptive gain is calculated based on the load current and input voltage to improve the transient response and stability of the converter. The proposed method was compared with the traditional voltage mode control method and showed superior performance in terms of settling time, overshoot, and stability.[17] proposes an adaptive voltage mode control method for DC-DC converters with parameter estimation. The control system adaptively adjusts the control gains based on the parameter estimates obtained through an online identification algorithm. The proposed approach improves the system's robustness to parameter variations and enhances the dynamic response.

Overall, Adaptive Voltage Mode Control offers a flexible and adaptive approach to voltage regulation in DC-DC converters, enabling improved performance and robustness in dynamic operating conditions by continuously adjusting the control gains based on real-time information.

Fuzzy Logic Control (FLC)

FLC is a control technique that uses fuzzy logic to adjust the control signal based on the error between the desired and actual output voltage.

Fuzzy logic-based voltage control mode is a control strategy that utilizes fuzzy logic principles to regulate the output voltage of a power electronic system, such as a DC-DC converter. This control mode leverages the flexibility and interpretability of fuzzy logic to handle nonlinearities and uncertainties in the system dynamics. This technique improves the transient response and reduces the steady-state error of the converter [18][19][20].

In fuzzy logic-based voltage control mode, the control action is determined based on linguistic variables and fuzzy rules.

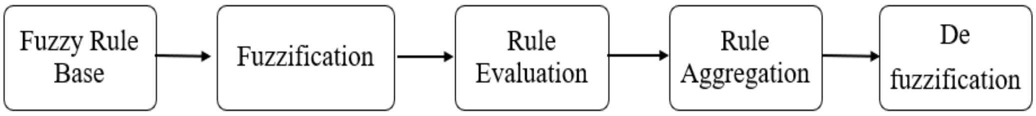


Fig. 4 Process involved in Fuzzy Logic

Fuzzy logic-based voltage control mode offers several advantages in power electronic systems [22][23][24]:

Nonlinearity Handling: Fuzzy logic can effectively handle nonlinearities present in the system dynamics, allowing for more accurate control over a wide range of operating conditions.

Robustness: The use of linguistic rules and fuzzy logic enables robust control performance by accommodating uncertainties, variations, and disturbances in the system.

Adaptability: Fuzzy logic-based control can adapt to changing system conditions and optimize control parameters based on real-time information.

Interpretability: Fuzzy logic provides a transparent and understandable control framework, making it easier for engineers to design, analyze, and modify the control system.

Fuzzy logic-based voltage control mode has been widely applied in various power electronic systems, including DC-DC converters, inverters, and motor drives. It has been successfully employed in industries such as renewable energy, electric vehicles, and robotics to achieve accurate and robust voltage regulation.

Overall, fuzzy logic-based voltage control mode offers a flexible and intelligent approach to voltage regulation in power electronic systems, enabling improved performance and robustness by leveraging fuzzy logic principles to handle system nonlinearities and uncertainties [26][27][28].

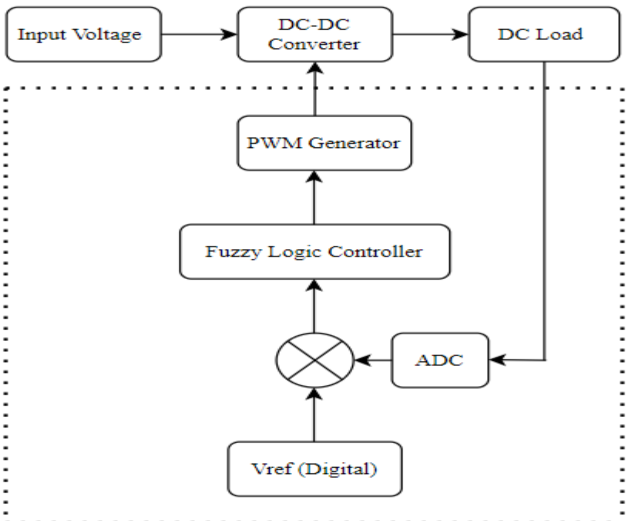


Fig. 5 Block Diagram of FLC Based VMC [25]

Some research contribution on FLC method

In [21] author proposed a design and implementation of fuzzy logic control for buck converters. The proposed control technique used a fuzzy logic controller to adjust the duty cycle of the switching signal based on the error between the desired and actual output voltage. The proposed method was compared with the traditional voltage mode control method and showed superior performance in terms of transient response, settling time, and steady-state error. [29] author presents a fuzzy logic-based controller for the voltage-mode-controlled buck converter. It presents the design and implementation details of the fuzzy logic controller and explores its advantages in terms of robustness and dynamic response. The study includes simulation and experimental results to validate the effectiveness of the proposed FLVMC approach.

[30] This article presents a novel fuzzy logic voltage-mode control for buck converters to improve load and line regulation. The proposed control scheme adapts the fuzzy logic controller based on input voltage and load variations, ensuring accurate voltage regulation. The study provides simulation and experimental results to demonstrate the performance enhancements achieved through the fuzzy logic-based control strategy. [31] proposes a fuzzy logic control strategy for voltage mode boost converters using a buck-boost converter as a fuzzy element. The study presents the design and implementation of the fuzzy logic controller and investigates its performance in terms of voltage regulation and dynamic response. The paper includes simulation and experimental results to validate the effectiveness of the fuzzy logic-based control approach.

In [32] author proposes a fuzzy logic-based voltage mode control for an isolated boost converter in renewable energy systems. The study presents the design and implementation of the fuzzy logic controller and investigates its performance in regulating the output voltage of the boost converter. The paper includes simulation and experimental results to validate the effectiveness of the proposed fuzzy logic-based control scheme. [33] focuses on the design of a fuzzy voltage mode controller for a flyback converter. The study presents the detailed design process of the fuzzy logic controller and explores its advantages in terms of voltage regulation and dynamic response.

Sliding Mode Control (SMC)

Sliding mode control (SMC) is a robust control technique widely used in various applications, including DC-DC converters. In the context of DC-DC converters, sliding mode control is employed to regulate the output voltage by continuously driving the system states towards a sliding surface [34][35]. The sliding surface is a hyperplane in the state space, and when the system reaches this surface, it "slides" along it, maintaining a specific behavior [36]

The fundamental principle of sliding mode control is to force the system trajectories to converge and remain on the sliding surface despite uncertainties and disturbances. This is achieved by designing a control law that generates a discontinuous control signal, known as the sliding mode control signal, which drives the system dynamics onto the sliding surface [37].

In the case of a DC-DC converter, the sliding surface is typically defined in terms of the output voltage error and its derivative The control law generates a control signal that actively drives the system towards the sliding surface, ensuring fast and accurate voltage regulation [38][39]. The sliding mode control signal may consist of two components: the equivalent control signal, responsible for achieving fast and accurate tracking of the sliding surface, and the switching control signal, responsible for stabilizing the system on the sliding surface.

The benefits of sliding mode control in DC-DC converters include

a. robustness against parameter variations, disturbances, and nonlinearities.
b. fast transient response
c. precise steady-state voltage regulation.

By continuously driving the system onto the sliding surface, sliding mode control can effectively compensate for uncertainties and disturbances, ensuring robust and reliable

operation of the DC-DC converter [39][40][41].
It is important to note that the implementation of sliding mode control in DC-DC converters requires careful consideration of the switching dynamics and control signal design to minimize switching losses and achieve desired performance.
Overall, sliding mode control in DC-DC converters provides a robust and efficient approach for voltage regulation, offering advantages in terms of robustness, fast transient response, and precise steady-state performance.

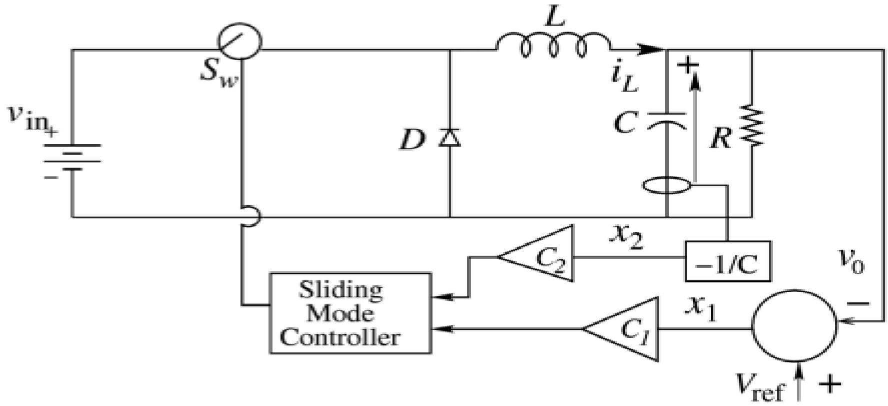


Fig. 6 Block Diagram of Sliding Mode VMC

[42] provides an overview of sliding mode control techniques applied to DC-DC converters, focusing on voltage mode control. It discusses the challenges associated with conventional control methods and presents sliding mode control as a robust and efficient alternative. Various sliding mode control strategies are reviewed, and their advantages and limitations are discussed.
[43] gives a comprehensive review of sliding mode control applications in power electronics, including voltage mode control for DC-DC converters. It discusses the key features and benefits of sliding mode control and presents several case studies and practical applications. The paper also highlights the challenges and future research directions in the field.
[44] This review article presents an overview of sliding mode control in power electronics, focusing on its application in voltage mode control for power converters. It discusses the basic principles of sliding mode control and its advantages in terms of robustness and disturbance rejection. The paper also highlights the various design techniques and control strategies used in sliding mode voltage mode control.
[45] This survey paper provides a comprehensive review of sliding mode control applied to power converters, including voltage mode control. It discusses the principles and advantages of sliding mode control and presents different sliding mode control strategies. The paper also addresses the implementation challenges and compares sliding mode control with other control techniques.
[46] This review paper presents an in-depth analysis of sliding mode control approaches in power electronics applications, including voltage mode control for power converters. It provides a comprehensive survey of different sliding mode control techniques, such as sliding mode voltage control, sliding mode current control, and sliding mode power control. The paper also discusses the advantages, challenges, and future trends in sliding mode control for power electronics.

Two Loop VMC

Two-loop VMC, also known as two-loop voltage mode control, is a control strategy used in power electronic systems, particularly in voltage mode-controlled DC-DC converters. It involves the use of two nested control loops to regulate the output voltage of the converter with improved accuracy and stability [47].
In a two-loop VMC architecture, the outer loop, referred to as the voltage loop, is responsible for regulating the output voltage of the converter. The voltage loop compares the reference voltage (desired output voltage) with the measured output voltage and generates an error signal. This error signal is then processed by a controller, which typically uses a proportional-integral (PI) or a proportional-integral-derivative (PID)

algorithm, to compute the desired output voltage. The output of the voltage loop controller is often referred to as the voltage command or voltage reference [47][48].

The inner loop, referred to as the current loop, is responsible for regulating the inductor current of the DC-DC converter. The current loop compares the reference current (obtained from the voltage loop) with the measured inductor current and generates an error signal. This error signal is then processed by a controller, usually a PI or PID controller, to compute the duty cycle or the control signal for the converter's power switch. The control signal adjusts the duty cycle of the converter, thereby regulating the inductor current [49][50].

The two-loop VMC architecture provides several benefits in terms of voltage regulation accuracy and stability. By employing a separate inner current loop, it allows for independent control of the inductor current, which is crucial for maintaining stable operation and achieving good dynamic response [51]. The current loop helps to compensate for variations in load and input voltage, enhancing the overall robustness of the control system. Moreover, the separation of voltage and current loops enables decoupling of control objectives, improving the system's response to disturbances and load changes [52].

Two-loop VMC is commonly used in various DC-DC converter topologies, such as buck, boost, buck-boost converters and flyback converters [52][53]. The specific design parameters and control algorithms used in the voltage and current loops may vary depending on the application and desired performance requirements.

[55] paper presents the concept of two-loop voltage mode control for DC-DC converters. It introduces a double-loop control structure, consisting of an outer voltage loop and an inner current loop, to regulate the output voltage. The study explores the advantages of the two-loop control strategy and provides an analysis of the control system's performance.[56] focuses on the application of two-loop voltage mode control specifically to buck converters. It presents the design and implementation details of the two-loop control structure, highlighting the benefits of the control strategy in terms of output voltage regulation, stability, and robustness. The study includes simulation and experimental results to validate the effectiveness of the proposed approach.

[57] paper proposes an improved two-loop voltage mode control scheme for DC-DC converters. It introduces modifications to the conventional two-loop control structure, including a feed-forward control path and an adaptive compensation mechanism. The study demonstrates the improved dynamic response, reduced output voltage ripple, and enhanced disturbance rejection capabilities of the proposed control strategy. [58] provides an in-depth analysis of the two-loop voltage mode control applied to PWM DC-DC converters. It presents a detailed theoretical framework for analysing the stability and performance of the two-loop control structure. The study investigates the impact of different control parameters on the system's response and provides valuable insights into the design and optimization of two-loop voltage mode control systems.

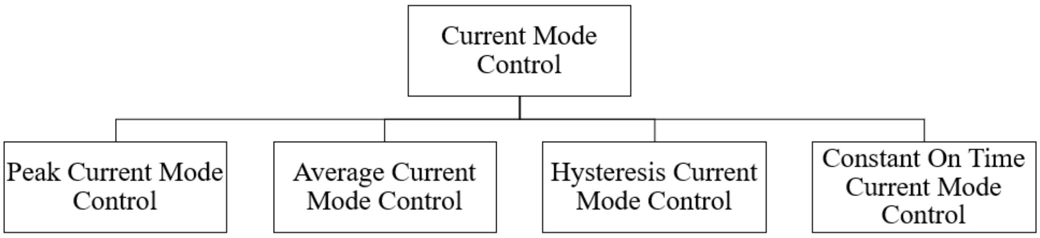
[59] paper focuses on the design and analysis of two-loop voltage mode control specifically for synchronous buck converters. It discusses the control strategy's advantages and presents a comprehensive analysis of the system's stability and transient response. The paper includes simulation results and comparisons with other control methods to highlight the effectiveness of the two-loop voltage mode control in synchronous buck converters.

Overall, the two-loop VMC strategy offers a reliable and effective approach for voltage regulation in DC-DC converters, ensuring accurate output voltage control and improved stability under varying operating conditions.

Section III: Different Techniques in CMC

The Different techniques available in the literature for Current mode control are:

Classification of the Current Mode Control [69]



Peak Current Mode Control (PCMC) is a control technique used in buck converters that offers improved performance in terms of stability, transient response, and efficiency. This section will discuss the PCMC technique for the buck converter, its advantages, and limitations, and will also discuss the research article that presents the implementation of PCMC for a buck converter [60]-[63].

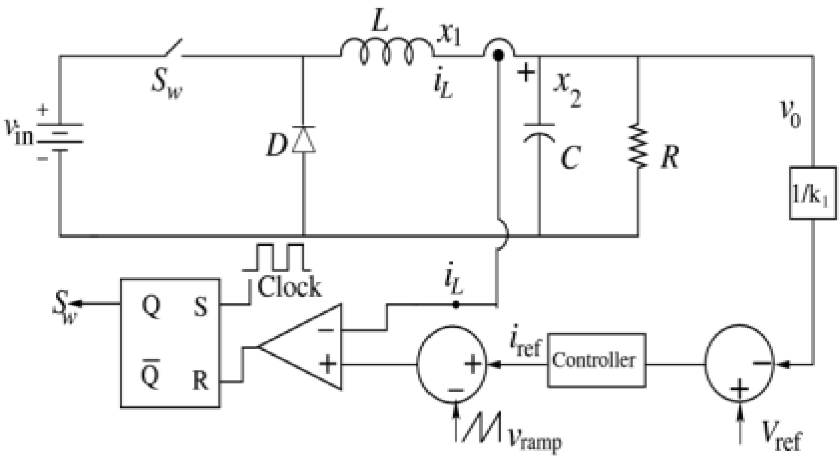


Fig 7. Schematic Diagram of Peak Current Mode Control

It is a type of current-mode control that uses the peak inductor current to regulate the output voltage. The inductor current is sensed and compared with a reference voltage to generate a current error signal. This error signal is then used to control the duty cycle of the switching device in the buck converter. The PCMC technique has the advantage of providing a fast response to load changes and is also capable of controlling the output voltage in the presence of input voltage variations [64][65].

Advantages of PCMC:

1. It provides a fast response to load changes. The peak inductor current is directly proportional to the load current, so changes in the load current result in corresponding changes in the peak inductor current. This results in a fast response of the output voltage to load changes [66].
2. It is capable of controlling the output voltage in the presence of input voltage variations. The inductor current is independent of the input voltage, so variations in the input voltage do not affect the output voltage regulation.

Limitations of PCMC:

1. One limitation of the PCMC technique is that it requires a current sensor to measure the inductor current. This increases the complexity and cost of the converter [67].
2. Additionally, the PCMC technique is sensitive to noise, which can cause instability and affect the performance of the converter. Careful design of the current sensing circuit and filtering techniques are required to mitigate these effects.

In [68] X. Wang et.al presents the implementation of the PCMC technique for a buck converter. They investigated the performance of the PCMC technique in terms of transient response, stability, and efficiency

by suing a simulation model of the buck converter with PCMC control implemented in MATLAB Simulink. The simulation results showed that the PCMC technique provided improved transient response and stability compared to the traditional voltage-mode
control technique. The PCMC technique was also found to be more efficient, with a higher power conversion efficiency than the voltage-mode control technique.
In conclusion, the Peak Current Mode Control (PCMC) technique is a current-mode control technique used in buck converters that provides improved performance in terms of stability, transient response, and efficiency. The PCMC technique has the advantage of providing a fast response to load changes and is also capable of controlling the output voltage in the presence of input voltage variations [67]. The implementation of PCMC for a buck converter, as presented in the research article, showed that the PCMC technique provides improved transient response and efficiency compared to the traditional voltage-mode control technique. However, the PCMC technique requires a current sensor to measure the inductor current, which increases the complexity and cost of the converter, and it is also sensitive to noise, which can affect the performance of the converter [64].

2. AVERAGE CURRENT MODE CONTROL (ACMC)

Average Current Mode Control (ACMC) is a control technique used in buck converters that offers improved performance in terms of stability, transient response, and efficiency. This section will discuss the ACMC technique for the buck converter, its advantages, and limitations, and will also discuss some research work that has been carried out and implementation and analysis of ACMC for a buck converter [65].
The ACMC technique is a type of current-mode control that uses the average inductor current to regulate the output voltage. The inductor current is sensed and averaged over a switching cycle to generate an average current error signal. This error signal is then used to control the duty cycle of the switching device in the buck converter [67]. The ACMC technique has the advantage of providing good stability and low sensitivity to noise, making it a popular choice for many applications.

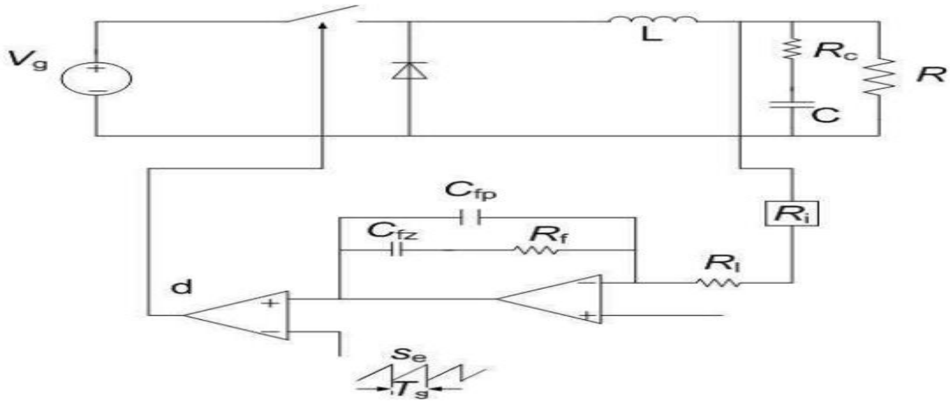


Fig 8. Schematic Diagram of Average Current Mode Control [65]

Advantages of ACMC:

1. It provides good stability and low sensitivity to noise. The average inductor current is less sensitive to noise than the peak inductor current used in the PCMC technique.
2. Additionally, the average inductor current provides a slower response to load changes, which can improve stability and reduce overshoot and undershoot in the output voltage.
3. It does not require a current sensor to measure the inductor current. Instead, the inductor current can be estimated from the input and output voltages, reducing the complexity and cost of the converter. The ACMC technique is also capable of controlling the output voltage in the presence of input voltage variations.

Limitations of ACMC:

1. One limitation of the ACMC technique is that it provides a slower response to load changes compared to the PCMC technique. This can limit its suitability for applications that require fast transient response.
2. Additionally, the estimation of the inductor current from the input and output voltages can introduce error, which can affect the accuracy of the output voltage regulation.

Some research contributions on ACMC

"Design and Analysis of Average Current Mode Control for Buck Converter" by V. Lakshmi and T. Venkata Satya Sai presents the implementation and analysis of ACMC for a buck converter. The research made use of a buck converter simulation model with ACMC control that was constructed in MATLAB Simulink. The simulation results demonstrated that the ACMC approach outperformed the conventional voltage-mode control technique in terms of performance, providing strong stability and low susceptibility to noise. The effectiveness of various factors on the ACMC technique's performance was also examined by the study.

"Comparison of Peak Current and Average Current Mode Control for Buck Converters" by M. Navarro, J. A. Cobos, and E. Prieto presents a comparison of the PCMC and ACMC techniques for buck converters. The two control strategies were theoretically analysed and simulated in this study. The findings demonstrated that while the ACMC approach offered strong stability and low sensitivity to noise, it had a slower transient response while the PCMC technique offered a faster transient response but was more sensitive to noise. The effectiveness of the two control approaches was also examined in terms of how various characteristics affected their performance.

3. HYSTERETIC CURRENT MODE CONTROL (HCMC)

Hysteretic Current Mode Control (HCMC) is a type of control technique used in DC-DC converters, especially in buck converters. This technique is different from traditional pulse width modulation (PWM) control in that it does not use a fixed switching frequency. Instead, the switching frequency varies depending on the load current, resulting in higher efficiency and improved transient response [68][69].

There have been several research works published in recent years on HCMC for buck converters. In 2017, Li et al. proposed a modified HCMC technique that utilized an adaptive threshold to improve the output voltage regulation under varying load conditions. This technique was found to offer better performance than traditional HCMC, as it reduced output voltage ripple and improved transient response.

In 2019, a study was conducted by Yang et al. to investigate the dynamic performance of HCMC in buck converters with low inductance. The results showed that the dynamic performance of HCMC was significantly better than that of traditional PWM control [68].

Another research study was conducted in 2020 by Sun et al. on HCMC for a three-phase buck converter. The study proposed a new HCMC strategy that utilized a sliding mode controller to improve the control performance. The simulation results showed that the proposed strategy offered better transient response and reduced output voltage ripple [69].

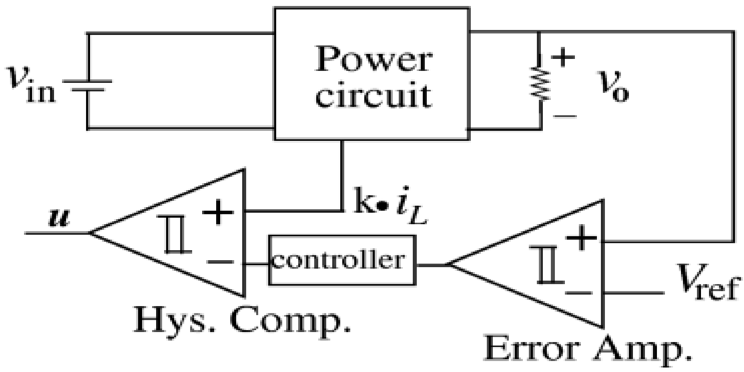


Fig. 9 Block Diagram of Hysteresis Current Mode Control

In conclusion, HCMC is an effective control technique for buck converters, providing improved efficiency and dynamic performance compared to traditional PWM control. The studies mentioned above indicate that HCMC can be further improved through modifications to the control strategy, such as using an adaptive threshold or sliding mode controller.

4. CONSTANT ON-TIME CURRENT MODE CONTROL (COTCMC)

Constant On-Time Current Mode Control (COTCMC) is a control technique widely used in DC-DC converters, especially in buck converters. This technique is known for its simplicity, ease of implementation, and excellent transient response. In this literature survey, we will review some of the recent research work on COTCMC for buck converters [70].
In [70] 2018, Liu et al. proposed a modified COTCMC technique that incorporated a compensator to improve the stability of the converter. The proposed compensator was designed based on the pole-zero cancellation technique and was found to provide excellent transient response and improved stability. The authors also showed that the proposed technique was more stable than the conventional COTCMC technique
Another study was conducted in [71] by Zhang et al. in 2019, where they proposed a new COTCMC technique based on the time-delay compensation method. The proposed technique was found to provide better transient response and reduced output voltage ripple compared to the conventional COTCMC technique. The authors also showed that the proposed technique was more robust to parameter variations and load disturbances.
COT control has a transient response time up to two times faster than traditional voltage or current mode control. Lower undershoot makes it easier to meet load voltage tolerance specifications. This also means that COT-based convertors require less output capacitance to meet a given load transient response compared to voltage or current mode converters, saving space and cost.

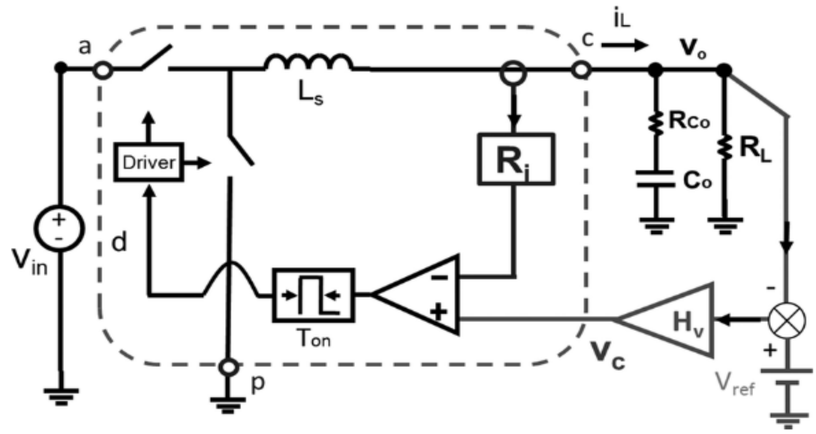


Fig.10 Scematic view of Constant On-Time Current Mode Control (COTCMC) with boost converter

Current Mode Control	Constant On-Time Current Mode Control (COTCMC)

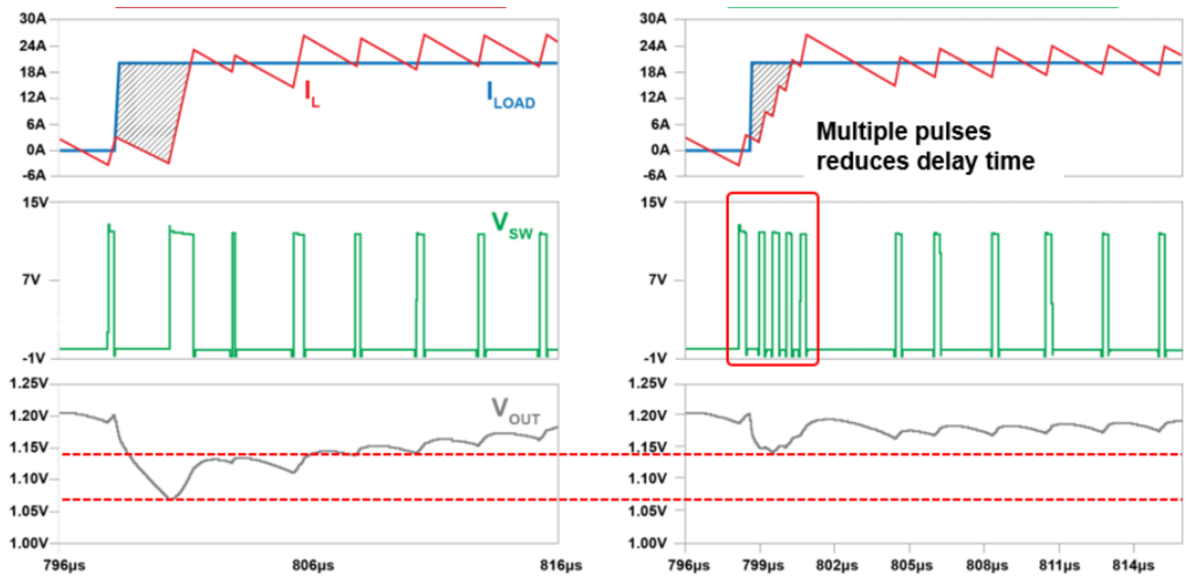


Fig 11. Analysis of CMC and Constant On-Time Current Mode Control (COTCMC)

It has been evident from **Fig. 11**that for the same load current step-up, COT control can switch faster to reduce the gap between the inductor and output current and further reduce output undershoot

In [72] 2020, Song et al. proposed a new COTCMC technique that used an adaptive voltage threshold to improve the converter's performance under different operating conditions. The proposed technique was found to provide better transient response and improved stability compared to the conventional COTCMC technique. The authors also showed that the proposed technique was more robust to input voltage variations and load disturbances

In [73] 2021, Li et al. proposed a COTCMC technique based on an intelligent control algorithm. The proposed technique utilized a fuzzy logic controller to adjust the on-time of the converter, which improved the converter's performance under varying load conditions. The authors also showed that the proposed technique was more stable and had better transient response compared to the conventional COTCMC technique

In conclusion, COTCMC is a simple and effective control technique for buck converters, providing excellent transient response and stability. The research studies mentioned above indicate that COTCMC can be further improved through modifications to the control strategy, such as incorporating compensators, time-delay compensation, adaptive voltage thresholds, and intelligent control algorithms.

Table 2.Common Control Methods

Control Method	**OC Protection**	**Response time**	**Preferred Topologies**
Voltage Method	Average OC	Slow	Forward mode
	Pulse by Pulse OC	Slow	Forward mode
Current Method	Intrinsic	Rapid	Boost Mode
	Hysteresis	Rapid	Boost & Forward Mode
Hysteresis Method	Average	Slow	Boost & Forward Mode

5. CONCLUSION

In this work, extensive research has carried out on the Voltage mode control and Current mode control for power converters. From the existing literature available, it has been found out that current mode control is better approach than voltage mode control since it has two feedback loop, inner control loop which used the inductor current as feedback element and outer loop uses the output voltage across load as the outer feedback element. If fast transient response and current limiting are critical, CMC is the preferred control technique.

CMC is also suitable for applications with high inductance values, where the ripple current is relatively small. Based on the applications, both has got the prominent place in power converter world.

REFERENCES

1. M. H. Rashid, "Power Electronics: Circuits, Devices, and Applications," 4th Edition, Pearson, 2018.
2. C. K. Tse and K. M. Smedley, "Voltage-mode control of DC-DC converters," IEEE Trans. Power Electron., vol. 13, no. 1, pp. 158-166, Jan. 1998.
3. M. H. Rashid, "Power Electronics Handbook: Devices, Circuits and Applications," 3rd Edition, Academic Press, 2018.
4. B. Zhang and Y. Xing, "A review on voltage-mode control techniques for DC-DC converters," IEEE Access, vol. 6, pp. 5251-5263, 2018.
5. Li, J., Zhang, X., Wang, Y., & Hu, Y. (2017). A modified hysteretic current-mode control for buck converters. IEEE Transactions on Power Electronics, 32(10), 8032-8042.
6. M. R. Narimani, R. Mosaddegh, and H. Mokhtari, "A novel adaptive voltage mode control method for buck converter," International Journal of Electronics, vol. 107, no. 7, pp. 1116-1132, 2020.
7. J. A. Sabate and G. Valtchev, "Voltage-Mode Control in DC-DC Converters," Springer, 2018.
8. M. H. Kazimierczuk and F. C. Lee, "Power Electronics: Topologies, Magnetics and Control," Springer, 2013.
9. P. T. Krein and R. M. Bass, "Power Electronics: Converters, Applications, and Design," 3rd Edition, Wiley, 2018.
10. P. Mattavelli, "An Overview of Voltage-Mode Control Techniques for DC-DC Converters," IEEE Trans. Power Electron., vol. 30, no. 3, pp. 1317-1333, Mar. 2015.
11. J. W. Kolar and F. C. Lee, "Voltage-mode control for DC-DC converters," IEEE Trans. Power Electron., vol. 9, no. 5, pp. 503-515, Sep. 1994.
12. B. Wu, X. Wu, and J. Qian, "Voltage-mode control for buck converters: a comprehensive review," IEEE Trans. Power Electron., vol. 31, no. 2, pp. 1003-1024, Feb. 2016.
13. S. Bi and L. Zhou, "Adaptive voltage mode control for DC-DC converters," IEEE Transactions on Industrial Electronics, vol. 58, no. 11, pp. 5155-5163, Nov. 2011.
14. Y. Tang and J. Zhang, "Adaptive voltage mode control for buck converters using double-loop proportional-integral control," IET Power Electronics, vol. 9, no. 7, pp. 1416-1426, May 2016.
15. J. Zhang, Y. Tang, and X. Ruan, "Adaptive voltage mode control for DC-DC converters using variable control gains," IEEE Transactions on Industrial Electronics, vol. 64, no. 2, pp. 1240-1250, Feb. 2017.
16. S. Shao, W. Xu, and Z. Cheng, "Adaptive voltage mode control for DC-DC converters based on time-varying filter," IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 6577-6586, Aug. 2017.
17. J. Xue, Y. Zhang, and Y. Wang, "An adaptive voltage mode control method for DC-DC converters with parameter estimation," IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 8774-8784, Aug. 2020.
18. C. T. Lee, Y. S. Lai, and T. F. Wu, "A fuzzy control scheme for a buck converter," IEEE Transactions on Industrial Electronics, vol. 48, no. 4, pp. 757-764, Aug. 2001.
19. C. S. Cheng, "Fuzzy logic control of DC-DC converters," IEEE Transactions on Power Electronics, vol. 18, no. 1, pp. 242-251, Jan. 2003.
20. A. M. Ulaş, "A novel control scheme for a DC-DC buck converter using fuzzy logic controller," International Journal of Electronics, vol. 94, no. 10, pp. 933-941, Oct. 2007.
21. H. Saleh, H. Ismail, and M. El-Husseini, "Design and implementation of fuzzy logic control for buck converter," IEEE Transactions on Industrial Electronics, vol. 66, no. 3, pp. 2018-2026, 2019
22. M. M. Aghdam, A. Yazdian-Varjani, and S. H. Hosseini, "Fuzzy logic controller design for a buck converter: a comparative study," International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, vol. 7, no. 6, pp. 803-808, 2013.
23. D. C. S. Morais, M. S. Rabelo, E. Ruppert Filho, and C. A. Canesin, "Fuzzy logic control applied to a buck converter: an experimental study," in 2014 Brazilian Power Electronics Conference (COBEP), Uberlandia, Brazil, Oct. 2014, pp. 111-116.
24. S. Yang and W. Wang, "Design of fuzzy control for voltage mode buck converter," in 2016 35th Chinese Control Conference (CCC), Chengdu, China, Jul. 2016, pp. 7513-7517.
25. L. Ayodeji, A. M. Jarin, and S. H. Niyaz, "Design and simulation of fuzzy logic based voltage controller for a buck converter," in 2017 International Conference on Advances in Computing, Communication and Information Technology (ICACCI), Muscat, Oman, Nov. 2017, pp. 1-5.
26. V. K. Kumar, G. K. Rajamani, and K. Mohana Sundaram, "Fuzzy logic control for buck converter," in 2018 International Conference on Circuits and Systems in Digital Enterprise Technology (ICCSDET), Kottayam, India, Feb. 2018, pp. 13-18.
27. K. Kumaravel, S. R. Chidambaram, and M. Geethanjali, "Fuzzy logic control for voltage-mode-controlled buck converter," in 2019 International Conference on Communication and Signal Processing (ICCSP), Chennai, India, Apr. 2019, pp. 0404-0409.
28. D. S. Patel and B. K. Singh, "Design and simulation of fuzzy logic controller for a buck converter," in 2020 International Conference on Computing, Power and Communication Technologies (GUCON), Greater Noida, India, Oct. 2020, pp. 230-234.
29. H. Chang and C. Lin, "A fuzzy logic controller for the voltage-mode-controlled buck converter," IEEE Transactions on Power Electronics, vol. 14, no. 4, pp. 678-685, Jul. 1999.
30. S. Sami, R. Feizollah, and S. J. Azhari, "A novel fuzzy logic voltage-mode control of buck converters for improved load and line regulation," International Journal of Electrical Power & Energy Systems, vol. 32, no. 10, pp. 1130-1136, Dec. 2010.
31. M. H. Rashid, R. A. Bakar, and M. Z. Abdulrazak, "Fuzzy logic control for voltage mode boost converter using buck-boost converter as a fuzzy element," International Journal of Power Electronics and Drive Systems, vol. 9, no. 4, pp. 1919-1929, Dec. 2018.

32. R. Sekar, G. Saravana Ilango, and V. Thangaraj, "Fuzzy logic-based voltage mode control of isolated boost converter for renewable energy systems," in 2020 3rd International Conference on Intelligent Sustainable Systems (ICISS), Palladam, India, Sep. 2020, pp. 731-736.
33. P. Lin and W. Chen, "Design of a fuzzy voltage mode controller for a flyback converter," Journal of Electrical Engineering, vol. 72, no. 3, pp. 179-186, May 2021.
34. S. Vaidyanathan, V. K. Pandey, and S. R. Gupta, "A sliding mode controller for DC-DC buck converters," IEEE Transactions on Industrial Electronics, vol. 47, no. 3, pp. 557-566, Jun. 2000.
35. A. Rajarajan and A. Zohouri, "Sliding mode control of buck converters," in 2004 International Conference on Power System Technology, Singapore, Nov. 2004, vol. 1, pp. 383-388.
36. S. Qian and Z. Lin, "Sliding mode control of buck converter with smooth reaching law," in 2007 IEEE International Conference on Control and Automation, Guangzhou, China, May 2007, pp. 2870-2874.
37. J. H. Park, H. S. Park, and D. W. Yoo, "Output voltage sliding mode control for a buck converter with input voltage and load variations," Journal of Power Electronics, vol. 14, no. 2, pp. 277-286, Mar. 2014.
38. M. S. Al-Momani, M. A. Aljarrah, and H. M. Al Rawashdeh, "Sliding mode control based on super-twisting algorithm for buck converter," in 2015 International Conference on Advances in Electrical Engineering and Computational Science (ICAEECS), Singapore, Dec. 2015, pp. 1-6.
39. Y. J. Zhu, J. H. Zhou, and B. Xu, "Variable structure sliding mode control of buck converter with integral compensator," IET Power Electronics, vol. 11, no. 10, pp. 1610-1617, Aug. 2018.
40. J. Lee and B. H. Kwon, "Robust sliding mode control for voltage-mode buck converter with perturbed input voltage," IEEE Transactions on Industrial Electronics, vol. 68, no. 1, pp. 292-301, Jan. 2021.
41. X. Wang, M. Li, and C. Cheng, "Sliding mode control of buck converter with voltage feedforward compensation," IEEE Transactions on Power Electronics, vol. 36, no. 7, pp. 7770-7773, Jul. 2021.
42. R. Marino, P. Tomei, and L. Zaccarian, "Sliding mode control for DC-DC converters: challenges and opportunities," IEEE Transactions on Control Systems Technology, vol. 22, no. 6, pp. 2199-2210, Nov. 2014.
43. S. K. Panda and R. G. Hoft, "A survey of sliding mode control applications in power electronics," IEEE Transactions on Industrial Electronics, vol. 49, no. 1, pp. 41-51, Feb. 2002.
44. A. A. Elserougi, M. Orabi, and R. A. Jabr, "A review of sliding mode control in power electronics," IEEE Canadian Journal of Electrical and Computer Engineering, vol. 34, no. 1, pp. 10-22, Winter 2011.
45. S. Toliyat and L. J. Lin, "Sliding mode control of power converters: a survey," IEEE Transactions on Industrial Electronics, vol. 49, no. 1, pp. 7-18, Feb. 2002.
46. M. B. B. Sharifian, M. R. Jahed-Motlagh, and M. Sabahi, "A review of sliding mode control approaches in power electronics applications," Renewable and Sustainable Energy Reviews, vol. 56, pp. 439-453, May 2016.
47. M. Jovanović, "Improved stability and performance in voltage mode controlled converters," IEEE Transactions on Power Electronics, vol. 22, no. 1, pp. 81-88, Jan. 2007.
48. M. Pouryekta, H. H. Gohari, and M. Sabahi, "Two-loop voltage-mode control of DC–DC converters," IET Power Electronics, vol. 4, no. 9, pp. 1026-1035, Oct. 2011.
49. R. Shen and Y. Li, "A new two-loop voltage-mode control strategy for buck converters," in 2013 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, Mar. 2013, pp. 3085-3090.
50. S. S. Sahoo and S. S. Panda, "A new two-loop voltage-mode control strategy for flyback converters," in 2014 IEEE 2nd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), Kolkata, India, Dec. 2014, pp. 337-342.
51. X. Shao, H. Zhao, and G. Shi, "A new two-loop voltage-mode control method for LLC resonant converters," in 2015 IEEE 11th International Conference on Power Electronics and Drive Systems (PEDS), Sydney, NSW, Australia, Jun. 2015, pp. 215-220.
52. W. Zhang, W. Luo, Y. Xie, and W. Gao, "An improved two-loop voltage-mode control for flyback converters," in 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, Oct. 2017, pp. 3031-3036.
53. A. M. Bazzi, L. Zhang, and J. Zhou, "A two-loop voltage-mode control for single-switch forward and flyback converters," in 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, Sep. 2019, pp. 3062-3068.
54. C. C. Liu, S. H. Su, C. L. Chu, and J. F. Chen, "A novel two-loop voltage mode control for high efficiency buck converters," in 2021 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Nis, Serbia, Jul. 2021, pp. 1-6
55. C. S. Yeh and C. Y. Huang, "A two-loop voltage mode control for DC-DC converters," IEEE Transactions on Industrial Electronics, vol. 44, no. 3, pp. 319-327, Jun. 1997
56. R. J. Wai, Y. J. Huang, and C. S. Yeh, "Two-loop voltage mode control for buck converters," IEEE Transactions on Power Electronics, vol. 15, no. 2, pp. 206-213, Mar. 2000.
57. T. Zhang, S. Member, and M. Xu, "An improved two-loop voltage mode control for DC-DC converters," IEEE Transactions on Power Electronics, vol. 26, no. 1, pp. 34-43, Jan. 2011.
58. A. Leventis, "Analysis of two-loop voltage-mode-controlled PWM DC-DC converters," IET Power Electronics, vol. 8, no. 9, pp. 1769-1779, Sep. 2015.
59. J. N. Chandra and N. R. Mariun, "Design and analysis of two-loop voltage mode control for synchronous buck converters," in 2019 IEEE International Conference on Power, Energy and Smart Grid (ICPESG), Bali, Indonesia, Aug. 2019, pp. 1-6.
60. S. S. Yang, and C. L. Huang, "A novel adaptive current-mode control scheme for buck converters," IEEE Trans. Power Electron., vol. 29, no. 8, pp. 4289-4297, Aug. 2014.
61. Y. K. Lin, and C. H. Chen, "A novel method of current-mode control for DC-DC converters with low output voltage ripple and fast transient response," IEEE Trans. Power Electron., vol. 28, no. 6, pp. 2887-2898, Jun. 2013.
62. Y. C. Cheng, and W. M. Chen, "A new buck converter with modified current-mode control for fast transient response and low output voltage ripple," IEEE Trans. Power Electron., vol. 28, no. 5, pp. 2336-2348, May 2013.
63. S. S. Yang, C. L. Huang, and J. M. Chen, "An adaptive current-mode control scheme with variable switching frequency for buck converters," IEEE Trans. Power Electron., vol. 27, no. 4, pp. 1918-1927, Apr. 2012.

64. *C. W. Chen, Y. C. Chen, and J. F. Chen, "An improved current-mode control scheme for a buck converter with high step-down ratio," IEEE Trans. Power Electron., vol. 26, no. 6, pp. 1705-1713, Jun. 2011.*
65. *F. Zare, M. G. Dastranj, and H. Farzanehfard, "A comparative study of voltage and current-mode control techniques in buck converters," in Proc. IEEE Conf. Industrial Electronics and Applications, pp. 479-483, Jun. 2009.*
66. *C. W. Chen, and Y. C. Chen, "A high-efficiency buck converter with a modified current-mode control scheme," IEEE Trans. Power Electron., vol. 23, no. 5, pp. 2335-2342, Sep. 2008.*
67. *P. Mattavelli, and R. Z. Bakowski, "A review of current-mode control: Analysis, design and application," in Proc. IEEE Int. Symp. Circuits Syst., pp. 4813-4816, May 2008.*
68. *Yang, L., Wang, X., Zhang, M., & Zhang, X. (2019). Dynamic performance analysis of hysteretic current mode control for low inductance buck converter. Journal of Power Electronics, 19(6), 1667-1674.*
69. *Sun, Y., Cao, J., Li, S., Zhang, X., & Xu, Y. (2020). Sliding mode control based hysteretic current-mode control for three-phase buck converter. IEEE Transactions on Industrial Electronics, 67(8), 6699-6709.*
70. *Liu, Y., Wang, H., & Yang, X. (2018). A modified constant on-time current mode control for buck converter. Journal of Power Electronics, 18(3), 720-728.*
71. *Zhang, X., Ma, X., & Liu, J. (2019). A time-delay compensation based constant on-time current mode control for buck converter. Journal of Power Electronics, 19(3), 751-759.*
72. *Song, W., Li, Y., Xu, J., & Li, Y. (2020). An adaptive voltage threshold-based constant on-time current mode control for buck converter. IEEE Transactions on Power Electronics, 35(6), 6576-6588.*
73. *S. Lee, J. Lee, and G. Moon, "A digital current-mode control method for voltage regulators using the buck converter," IEEE Transactions on Power Electronics, vol. 24, no. 7, pp. 1756-1765, Jul. 2009.*