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Comparative Analysis of Fixed Frequency Current Mode Control and Variable Frequency Hysteresis Current Mode Control in Terms of Transient Performance

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***Abstract*— This paper primarily presents two modulation methods implemented in a buck converter: fixed frequency Current Mode Control (CMC) and variable frequency Hysteretic Current Mode Control (HCMC). The main objective is to study the operation of these two control topologies and demonstrate their transient responses. The focus on HCMC and CMC of the buck converter is intended to analyze their transient responses under line and load disturbances. Mathematical equations of a buck converter are developed, and these two modulation methods are implemented to explore their transient performance. Therefore, simulation studies are performed on the buck converter to observe which modulation method copes with the transient state faster and reaches a steady-state condition.**

***Keywords*— Dc-dc buck converter, CMC, HCMC, Transient response,**

I. INTRODUCTION

DC-DC converters are essential in powering electronic circuits and managing energy transfer between DC systems. They are widely used across various industries where stable voltage is essential. Recently, the transient performance of power supplies has become a key factor in the efficient operation of microprocessors and portable electronic devices [1-3]. This growing importance highlights the need for effective transient response in DC-DC power supplies. Although linear regulators can improve transient response, their reduced efficiency makes them unsuitable for high-current applications. Conversely, while standard switching regulators offer better efficiency, their slower transient response requires large load capacitance. In power electronics converters, nonlinearities are frequently encountered[7]. A comparative study has been conducted on the nonlinear behavior of different modulation methods such as current mode control and hysteresis current mode control in SEPIC converter[4], and capacitor compensated V2 control with peak current mode control in buck converter[5].

In [6] a HCC (Hysteresis current control) buck converter that integrates a PLL (phase-frequency-locked loop) to stabilize the switching frequency in Continuous Conduction Mode (CCM). This modification is intended to enhance efficiency and mitigate switching frequency fluctuations. Various variations of hysteresis control topology implemented in a buck converter[8-10]

In this paper, we elaborate on the operation of a fixed-frequency CMC and a variable-frequency HCMC. These two control methods are applied to a buck converter, demonstrating their rapid response to load and line disturbances. The structure of the paper is as follows: Section II outlines the operational principles of both the CMC (current mode control) and HCMC (hysteresis current mode control). Section III details the mathematical equations of the system, including transient analysis under varying load and line conditions, and provides a comparative study of their transient responses. Section IV presents the conclusions drawn from our analysis. All simulations were performed using MATLAB Simulink.

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II. OPERATING PRINCIPLE

A. Current mode control(CMC)

A peak current-mode modulation method, represented in Fig. 1, essentially consists of two feedback paths: an inner-current loop, also known as the fast feedback path, and an outer-voltage loop, also known as the slow feedback path. In the outer loop, the output voltage V_o is measured and compared with a fixed reference voltage to generate an error signal V_{error} . In the inner loop, the inductor current is sensed using a sensing resistor R_S to generate a signal V_P.

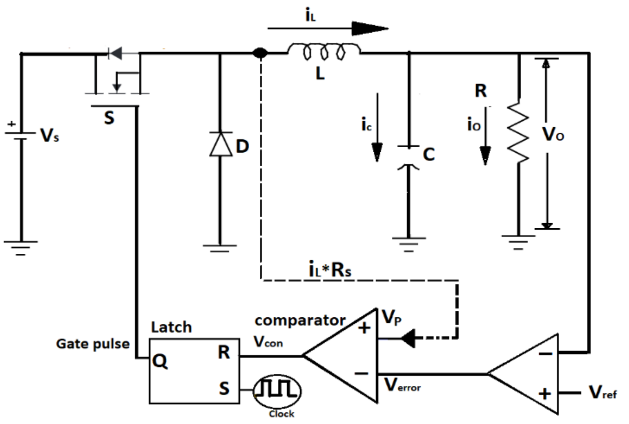

Fig.1: Current Mode Controlled Buck Converter

For controlling the switching action of the MOSFET S, a switching signal i.e. Gate pulse is generated by comparing V_P with V_{error} using a comparator, and this signal is then fed to the switch through an SR latch . At the onset of a switching cycle, the flip-flop is triggered by the clock signal (q=1), activating the MOSFET switch. During this phase, the switch current, which mirrors the i_L (inductor current), grows linearly. The sensed i_L is then compared with the error signal, V_{error}, from the controller. Once V_P marginally surpasses V_{error}, the comparator output transitions high, resetting the flip-flop (q=0) and subsequently deactivating the switch. This cycle repeats with the switch being reactivated by the subsequent clock signal, perpetuating the same process. The switch remains in the on state (i.e., V_{con} is low) as long as $V_P<V_{error}$. The switch S shifts to the off state (i.e., V_{con} is high) when $V_P \geq V_{error}$.

Figure 2 shows the simulation waveforms of the control signal, gate pulse, and clock signal for the CMC buck converter. From the graph, we can observe that

$V_P<V_{error}$	S-on state (Gate pulse high)
$V_P \geq V_{error}$	S-off state (Gate pulse Low)

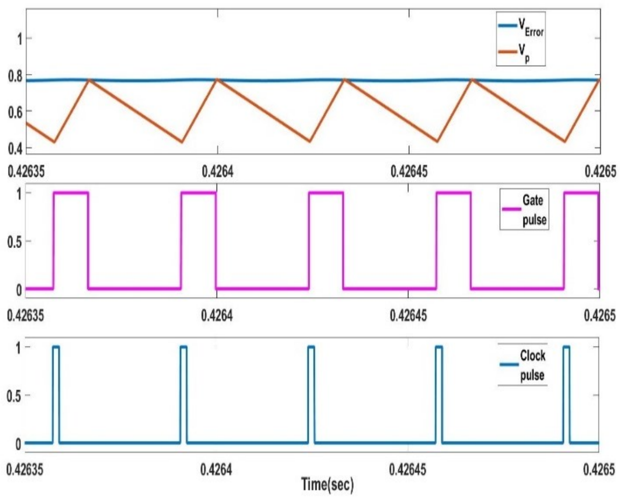

Fig. 2. Simulation waveforms of the control signal, gate pulse, and clock signal for a CMC-controlled buck converter

B. Hysteretic Current mode control(HCMC)

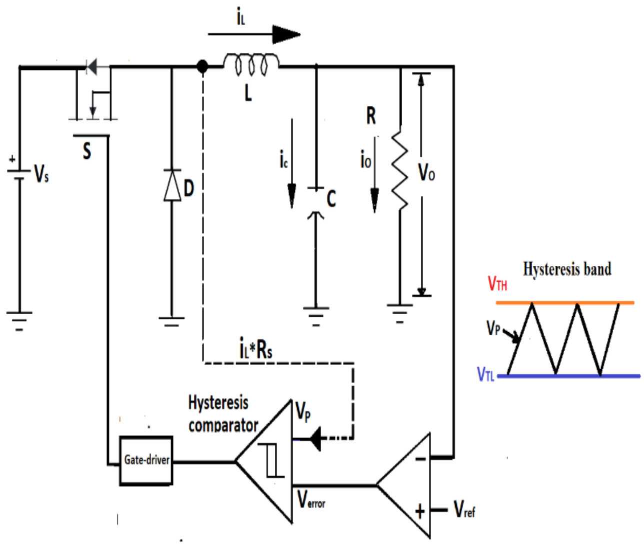

Fig.3. Hysteretic Current Mode Controlled Buck Converter

HCMC is a dynamic method used in power electronics to maintain the desired output of a system, typically in power supplies and converters. The principle behind hysteretic control is to keep the system's output within a predefined range or band, known as the hysteresis band, by rapidly switching the power MOSFET on and off.

In a typical implementation, the system continuously monitors the output current or voltage, allowing the control circuit to respond almost instantaneously to any deviations from the desired output level.

Fig. 3 represents a buck converter with a variable frequency hysteretic current mode control. In this scenario, in the inner loop, the inductor current is continuously sensed using a sensing resistor R_S to generate a signal V_P , which is compared with a hysteresis band. The outer loop contains the same information as CMC. The hysteresis band is defined around this reference voltage. When the sensed inductor current ($i_L \times R_S = V_P$) reaches the upper threshold (V_{TH}) of the

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band, the control circuit turns off the switch S, reducing the energy supplied to the output and causing the output level to drop. Conversely, when the V_P drops to the lower threshold (V_{TL}), the control circuit turns the power MOSFET back on, increasing the energy supplied and raising the output level. This method ensures that the output remains within the hysteresis band, oscillating around the desired level. This switching action maintains the sensed inductor current within the desired range, ensuring that the output voltage remains stable.

Figure 4 shows the simulation waveforms of the higher threshold voltage (V_{TH}),lower threshold voltage (V_{TL}) ,V_P and the gate pulse for the HCMC buck converter. From the graph, we can observe that

$V_P \geq V_{TH}$ S-off state (Gate pulse Low)

$V_P \leq V_{TL}$ S-on state (Gate pulse high)

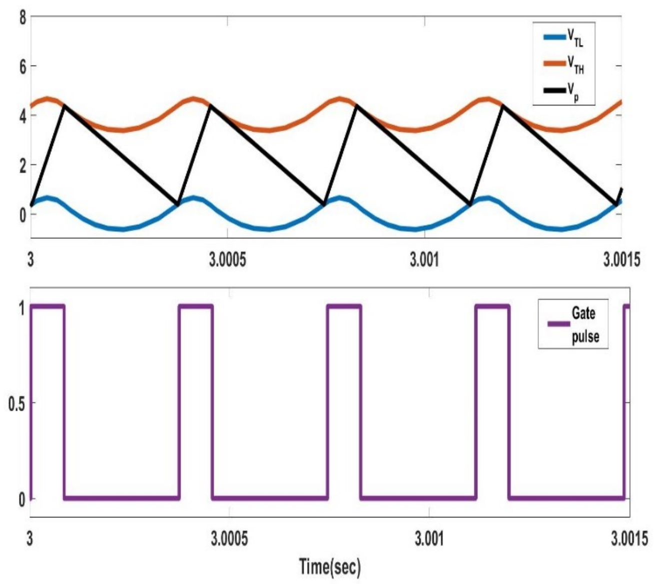


Fig.4. Simulation waveforms of the control signal and gate pulse, for a HCMC-controlled buck converter.

III. SIMULATION RESULTS AND DISCUSSION

Formulations for the mathematical equations in both CCM and DCM (Discontinuous Conduction Mode) have been established for the buck converter. Below are the equations that describe the on and off states of switch S and diode D.

Operational State (CCM): MOSFET (S) -on, Diode (D) -off

$$V_S = L\frac{di_L}{dt} + v_c \quad (1)$$

$$i_L = \frac{1}{L}\int(V_S - v_c) \quad (2)$$

$$i_c = i_L - i_o \quad (3)$$

$$\frac{1}{c}\int\left(i_L - \frac{v_c}{R}\right) = v_c \quad (4)$$

Operational State (CCM): MOSFET (S) -off, Diode (D) -on

$$v_c = -L\frac{di_L}{dt} \quad (5)$$

$$i_L = \frac{1}{L}\int(-v_c) \quad (6)$$

$$i_c = i_L - i_o \quad (7)$$

$$\frac{1}{c}\int\left(i_L - \frac{v_c}{R}\right) = v_c \quad (8)$$

Operational State (DCM): MOSFET (S) -off, Diode (D) -off

$$i_L = 0,\ i_c = -i_o \quad (9)$$

$$\frac{1}{c}\int\left(-\frac{v_c}{R}\right) = v_c \quad (10)$$

To perform the simulation operation of the buck converter with both CMC and HCMC, the following parameter values are considered:

Table-1 parameters list

Parameter	Valus
V_S	15V to 20V
L	0.4mH
C	1000µ F
V_{ref}	5V
R	10Ω to 20Ω
Switching frequency	30Khz (for CMC)

Both modulation methods are implemented in a buck converter using the same parameters mentioned in Table 1. We focus primarily on two types of disturbances: load variation and input voltage variation. Using various simulation graphs, we verify which modulation method quickly adapts to changes in system parameters and stabilizes the system.

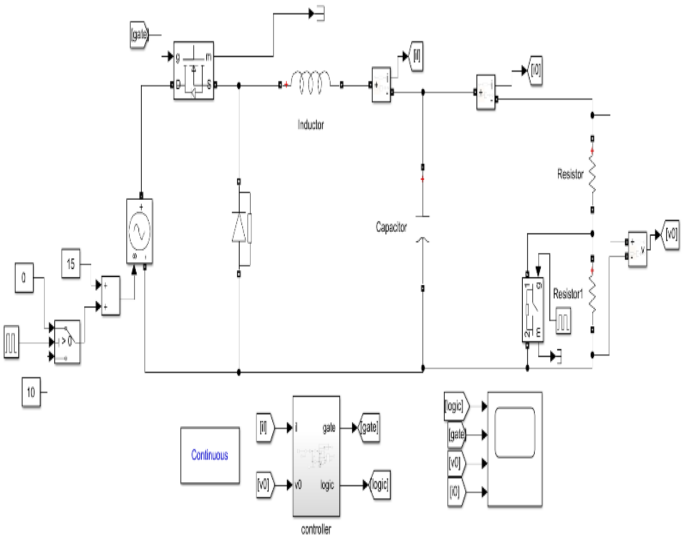
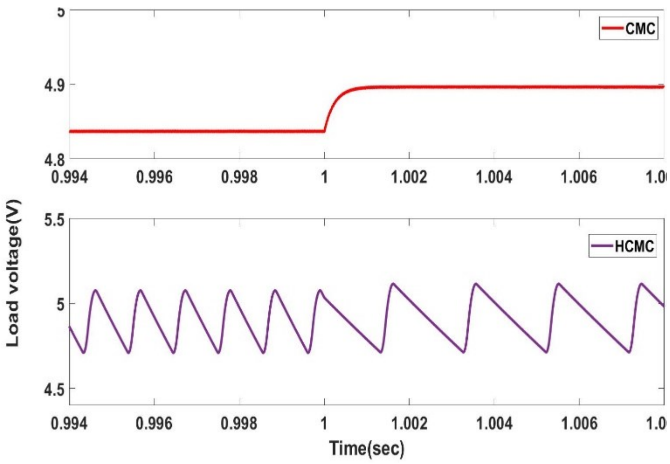


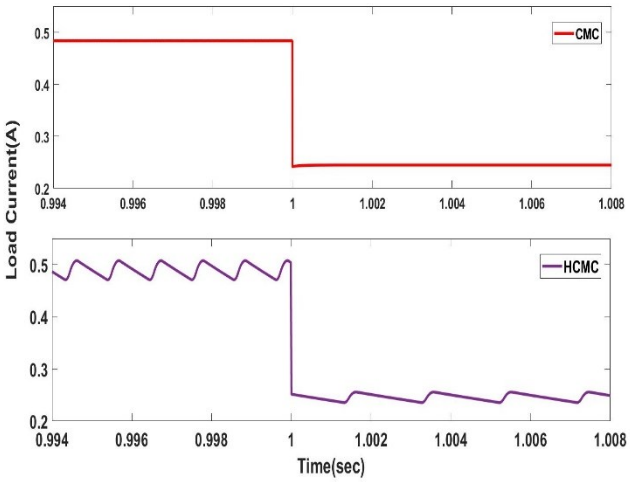
Fig.5. Simulink model of hysteretic current mode control buck converter

A. Exploring the effects of load disturbances on Transient performane

The transient performance of the buck converter is investigated under varying load resistances within a certain range. The responses of both modulators to sudden changes in load resistance and their efforts to stabilize the system are observed. The transient behaviors of the load voltage and current through the load (Fig. 6(a)and (b)) are recorded for both controlled converters. Here, all parameters are considered from Table 1, and the supply voltage is set at 20V.



(a)



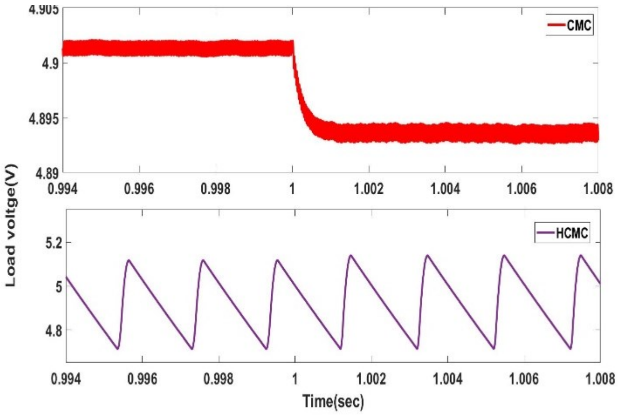
(b)

Fig.6. (a)Load Voltage with time (b) Load Current with time CMC & HCMC for Load disturbances (when load changes from 10 Ω to 20 Ω)

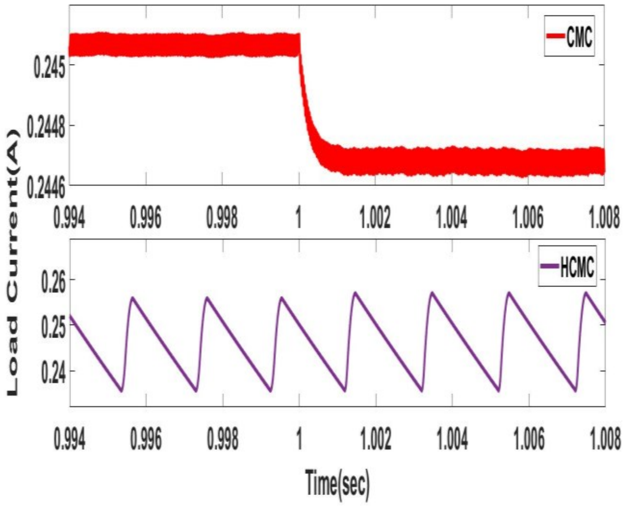
Initially, both systems operate under steady-state conditions. At this moment, the magnitude of the V_o (output voltage) and i_o (current through the load) are 4.838V and 0.4837A for the CMC system, and 5.077V and 0.5075A for the HCMC system. At 1 second, the load resistance changes from 10Ω to 20Ω. After the load disturbance, the new magnitudes of the load voltage and load current are 4.897V and 0.2449A for the CMC system, and 5.117V and 0.2557A for the HCMC system. Since the reference voltage is set to 5V, both controllers try to maintain the output voltage as close to the reference voltage as possible. Specifically, HCMC takes only 0.0003 seconds to settle down and reach its steady-state value, while CMC requires 0.002 seconds for the same process.

B. Exploring the effects of line disturbances on Transient performance

The transient behavior of the buck converter is analyzed under different input voltage conditions. Using parameters specified in Table 1, the load resistance is set at 10Ω. Figure 7(a) and (b) illustrate the transient responses of the volage across load resistance R and current through R for both the CMC and HCMC buck converters.



(a)



(b)

Fig.7. (a)Load Voltage with time (b)Load Current with time HCMC & CMC for Line disturbance (when supply voltage changes from 15V to 20V)

Initially, both systems are in steady-state conditions, with the V_o and i_o at 4.902V and 0.2451A for the CMC system, and 5.115V and 0.2558A for the HCMC system. At 1 second, the input voltage shifts from 15V to 20V. Following this disturbance, the new load voltage and current are 4.894V and 0.2447A for the CMC system, and 5.138V and 0.2569A for the HCMC system. With a reference voltage set to 5V, both controllers strive to keep the output voltage as close to the reference as possible Simulation results reveal that HCMC achieves a faster transient response. Specifically, HCMC takes only 0.00002 seconds to settle down and reach its steady-state value, while CMC requires 0.001 seconds.

IV. CONCLUSION

This paper offers a concise overview of two control methodologies, specifically current mode control and hysteretic mode control, implemented in DC-DC buck converters. It presents simulation results for each control method and conducts a comparative study between them. The comparison primarily focuses on the transient response characteristics of both control methods (CMC & HCMC) under variations in line voltage and load. Based on the transient response analysis, Overall, the HCMC buck converter consistently outperformed the CMC buck converter in terms of transient response time and stability under both load and input voltage variations. This makes HCMC a more effective choice for applications requiring rapid adaptation to changing conditions and robust performance stability.

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