



# Based on the Buck Circuit, Precise Regulation of Output Voltage is Achieved from Closed-loop control to Compound Control

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**Abstract.** With the advent of the new energy era, the requirements for power supply voltage regulation accuracy and dynamic response in high-precision equipment are becoming increasingly strict. As a core step-down topology, the Buck circuit has extensive applications in solar power generation, electric vehicle charging and discharging, and other fields. However, its traditional open-loop control has inherent defects such as large output voltage deviation and slow recovery. This study is based on the design of voltage closed-loop feedback and compound control. Through SIMULINK simulation comparison, it is verified that the closed-loop PI control can stably output voltage accuracy to  $\pm 0.5\%$ , significantly improving the anti-disturbance performance. The composite control design with feedforward compensation has reduced the recovery time by 56%, achieving a collaborative breakthrough of high precision and fast response. Finally, this article compares the advantages and disadvantages of the three types of control and looks forward to the directions of high frequency, intelligence and systematization. The aim is to enhance the output voltage accuracy, dynamic response and anti-interference capability of the Buck converter under complex working conditions.

**Keywords:** Open-Loop Control, Closed-Loop Control, Compound Control, Buck Circuit.

## 1 Introduction

With the continuous improvement of the requirements for power supply voltage stability in scenarios such as wind power generation and new energy electronic control systems, problems such as large output voltage deviation and long recovery time of Buck circuits under the control of traditional open-loop systems urgently need to be optimized and solved [1, 2]. R. D. Middlebrook and Slobodan Cuk proposed the state-space averaging method in 1976, laying the foundation for the modeling of switching power supplies [3]. Lu Jiaqi conducted simulation modeling of the Buck circuit using the PID control method. The results showed that the performance obtained by prioritizing the adjustment of the proportional coefficient of the PID was better [4].

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S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,

[https://doi.org/10.2991/978-94-6463-986-5\\_74](https://doi.org/10.2991/978-94-6463-986-5_74)

Mohsin Asad proposed an optimization method for dynamic dead time of GAN-based Buck converters. By adopting a mixed-signal control strategy to adaptively adjust the dead time, the peak efficiency of the converter is increased to 97.3% at a 1MHz switching frequency, while the light-load loss is reduced by 41.6%. This can effectively solve key problems such as body diode conduction and switching oscillation in high-frequency applications [5]. In this study, closed-loop feedback [6] was introduced to simulate the dynamic error and the variation curves of output voltage over time. The results show that the introduction of closed-loop feedback can improve the output voltage accuracy to  $\pm 0.5\%$ . Meanwhile, a composite control architecture combining feedforward compensation and closed-loop feedback was proposed. Through simulation, it can be seen that this design significantly shortens the output voltage recovery time. Finally, the advantages and disadvantages of open-loop control and closed-loop control are compared and explained, and the development direction of Buck circuits is prospected. It is hoped that Buck circuits with nanosecond response, low component voltage drop, and intelligent fault prediction can be developed to promote the continuous development of power electronics technology [7-10].

## 2 The basic working principle of the Buck circuit

The Buck circuit is a step-down DC-DC conversion circuit, The topology of its circuit is shown in Figure 1. It is mainly composed of a DC power supply, a switching tube (MOSFET tube is adopted in this paper), a freewheeling diode, an inductor, a capacitor and a load. When the MOSFET is turned on, both the inductor and the capacitor absorb energy simultaneously. The inductor current increases, and the capacitor starts to charge. At this time, the capacitor maintains the output voltage to ensure the stability of the output current. When the MOSFET tube is turned off, the inductor begins to release energy, the inductor current gradually decreases, and the freewheeling diode conducts. Together with the capacitor and the load, they form a freewheeling circuit. At this time, the inductor and the capacitor jointly maintain the stability of the output voltage. The Buck circuit, through continuous charging and discharging processes, regulates the output voltage by adjusting the duty cycle of the MODFET to achieve voltage reduction [11]. When the circuit is working in a stable state, the above two processes are repeatedly executed. During these two processes, the electrical energy generated by the power source and the electrical energy consumed by the load are equal, so the current values are the same at the beginning and end of the rise and fall. Through the filtering effect of the capacitor, the voltage on the load can be maintained at a relatively stable value, which can be expressed as:

$$V_{out}=V_{in}D \quad (1)$$

In the formula,  $V_{in}$  represents the input voltage of the Buck circuit;  $D$  represents the duty cycle of the MOSFET in the Buck circuit.

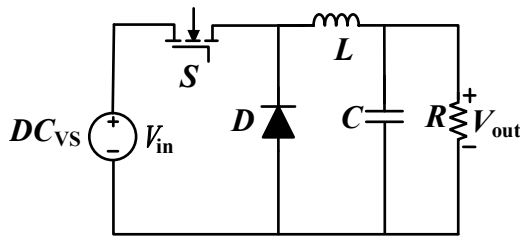
$$D = \frac{T_{on}}{T_{on}+T_{off}} \quad (2)$$

In the formula,  $T_{on}$  represents the conduction time of the MOSFET tube within one cycle.  $T_{off}$  is the conduction time of the MOSFET tube within one cycle.

Meanwhile, the circuit parameters are given in this paper, and all simulations are carried out based on these parameters. The circuit parameters are shown in Table 1.

**Table 1.**Buck Circuit Parameter Table

Parameter	Value
Input voltage $V_i$	50 V
Output voltage $V_0$	20 V
Inductance $L$	400 $\mu$ H
Capacitance $C$	100 $\mu$ F
Switching frequency $f$	20 kHz
Load resistance $R$	20 $\Omega$



**Fig. 1.** Basic schematic diagram of the Buck circuit

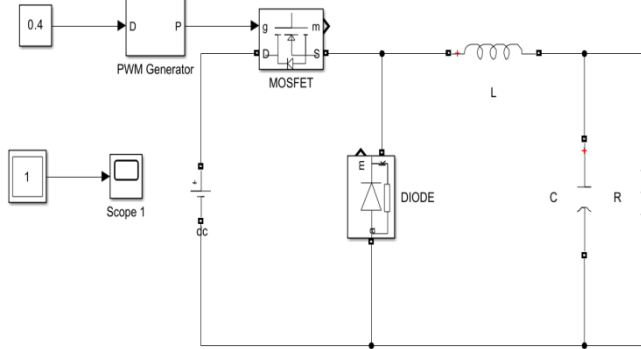
### 3 Pulse modulation mode

To control the conduction and turn-off of a MOSFET, a pulse signal needs to be applied. In this paper, PWM pulse width modulation technology is used, and its working principle is as follows: Subtract a carrier wave from a modulated wave. The resulting result is then compared logically with 0. If it is greater than 0, the output is positive; otherwise, it is negative. In this scheme, the modulation wave is the desired duty cycle, and the carrier can be either a Saw Tooth Wave or a Triangular Wave. In SIMULINK, there is a simple method, which is to directly use the PWM generator. This method only requires inputting the duty cycle and switching frequency. The simulation in this article uses this method.

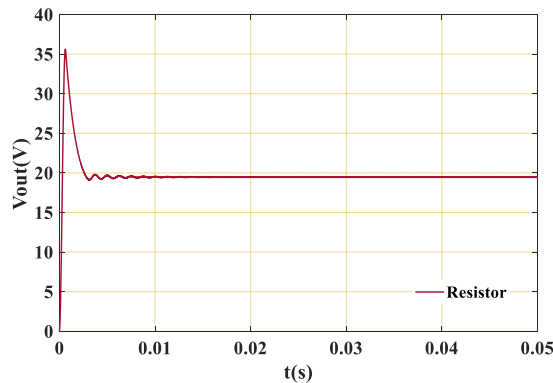
### 4 Open-loop control simulation

First, a PWM generator was directly used to build an open-loop controlled Buck circuit, as shown in Figure 2. The simulation results are shown in Figure 3: The image stabilizes around 20V but does not reach 20V, resulting in a steady-state error. The reason for such a result is that when the MOSFET is on, there is an on-resistance, which causes a voltage drop across the MOSFET and reduces the output result. In actual circuits, passive components such as inductors and capacitors have parasitic parameters that

affect the magnitude of the output voltage. In the freewheeling circuit, there is also a conduction voltage drop for the freewheeling diode. To accurately achieve an output of 20V, a large number of experiments need to be conducted by increasing the duty cycle to make the output voltage reach 20V. When the load changes, the experiments need to be repeated. Therefore, introducing closed-loop feedback to solve this problem can cope with any changes.



**Figure 2.** Simulation schematic diagram of open-loop control in Buck circuit



**Figure 3.** Diagram of the variation of the output voltage of open-loop control over time

## 5 Closed-loop control simulation

As shown in Figure 4, a simulation diagram of the closed-loop control Buck circuit has been built. In a closed-loop control system, the core is to have a given signal and a feedback signal compared to obtain a dynamic error, ensuring that the system can perceive changes in the output state. Subsequently, the PID controller dynamically adjusts the duty cycle of the MOSFET tube based on the error signal to further correct the output voltage [12]. The given signal is the desired output voltage, that is, a 20V signal, and the feedback signal is the actual output voltage. This paper simulates the

dynamic error and output voltage respectively. The simulation images are shown in Figure 5 and figure 6. It can be seen from the images that the error signal gradually approaches 0, and the output voltage also reaches 20V.

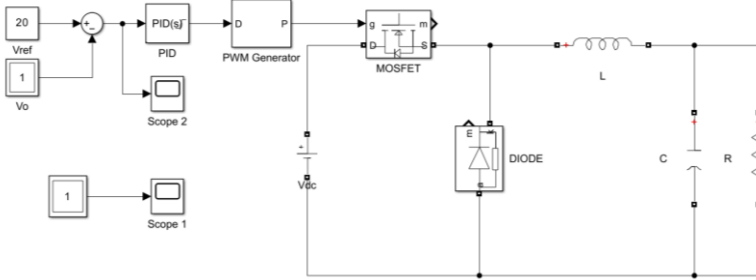


Figure 4. Simulation schematic diagram of closed-loop control in the Buck circuit

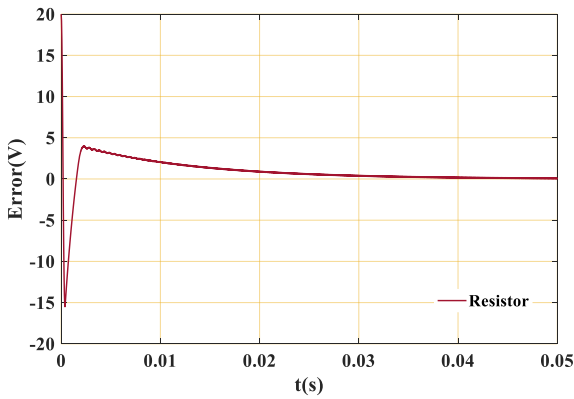


Figure 5. Graph of dynamic error varying with time under closed-loop control

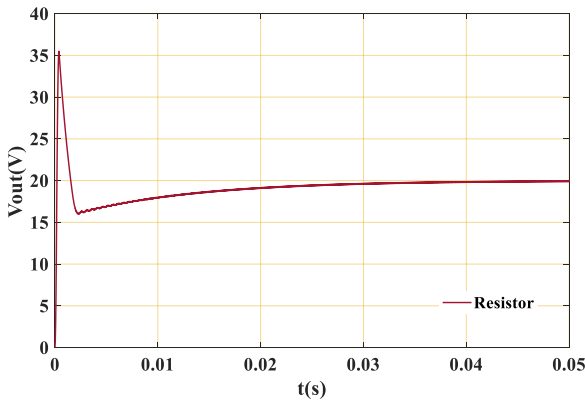
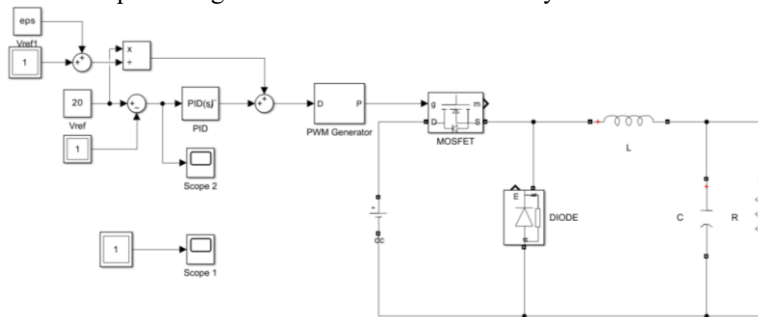


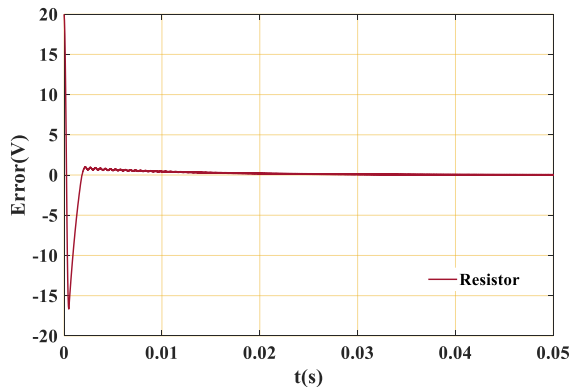
Figure 6. Output voltage variation over time under closed-loop control

## 6 Compound control simulation

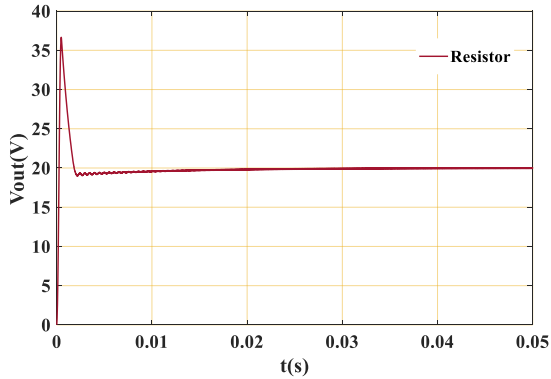
Although the output voltage reached 20V, problems emerged as well. The time to reach a steady state was long and slow. To address this issue, this paper introduces compound control, which combines open-loop control with closed-loop control, as shown in figure 7. Open-loop control is feedforward and can be regarded as a large signal, serving as a steady-state operating point. Based on disturbance prediction, it pre-compensates for known disturbances. Closed-loop control serves as feedback and can be regarded as a small signal, disturbing around the steady-state operating point. The output deviation is detected in real time by sensors, and the control quantity is dynamically corrected. Its duty cycle is composed of the duty cycle of open-loop control and that of closed-loop control. The ideal duty cycle of open-loop control is the input voltage above the ideal output voltage, which is then added to the duty cycle of closed-loop control to form the duty cycle of compound control. Through simulation, the graphs of dynamic error and output voltage varying with time were obtained, respectively, as shown in Figure 8 and figure 9. Analysis of the image shows that both the time for the error to reach zero and the time for the output voltage to stabilize have advanced by 0.02 seconds.



**Figure. 7.** Simulation Schematic diagram of the compound control of the Buck circuit



**Figure. 8.** Graph of dynamic error varying with time under compound control



**Figure. 9.** Output voltage variation over time under compound control

## 7 Comparison of advantages and disadvantages

The open-loop control system has a simple structure, does not require the design of feedback devices such as sensors and comparators, has a relatively low period cost, and is economically viable [13]. The system parameters only need to be adjusted according to the preset input-output relationship, without the need to handle the dynamic matching issue between the feedback signal and the controller, making the debugging process simpler. However, open-loop control systems cannot detect errors nor correct them. The control accuracy and the ability to suppress interference are relatively poor, and it is very sensitive to changes in system parameters.

The closed-loop control system fully leverages the crucial role of feedback, eliminating unpredictable or uncertain factors. Whether it is internal disturbances or changes within the system, as long as the controlled quantity deviates from the specified value, corresponding controls will be generated to eliminate the deviation. It has the ability to suppress interference and is insensitive to changes in the characteristics of components. However, the introduction of feedback loops increases the complexity of the system, and improper gain selection can cause instability in the system.

Compound control combines open-loop control and closed-loop control, featuring both high dynamic performance and strong robustness. Feedforward control can improve the response speed by compensating for measurable disturbances in advance based on model prediction, and feedback control can correct errors in real time to ensure the steady-state requirements. However, this control method is complex in design and difficult to set parameters, and it relies on precise modeling. Moreover, the feedforward channel is sensitive to parameter mismatch, and modeling errors will reduce the compensation effect.

Table 2 compares and summarizes the advantages and disadvantages of the three control methods. As shown in the table, although the compound control combines the advantages of open-loop control and closed-loop control, there are still technical bottlenecks. In the future, it needs to be further improved through intelligent algorithm optimization and new topological structures.

**Table 2.** Comparison Table of Advantages and Disadvantages of Three Control Methods

Control mode	Advantages	Disadvantage
Open-loop control	Simple structure, low cost, no stability issues	It has no anti-interference ability, poor control accuracy
Closed-loop control	Strong anti-interference ability, automatic error correction	The response is slow, stability analysis is required
Compound control	High dynamic performance, strong robustness, high precision	The design is complex, costly, relies on precise models

## 8 Conclusion

This study verified through Simulink simulation that the introduction of closed-loop control in the Buck circuit can significantly improve the voltage accuracy to  $\pm 0.5\%$  or even lower, effectively suppressing input fluctuations and load disturbances. By further introducing a composite control strategy that combines feedforward and feedback, the load step recovery time was shortened from 0.045 seconds in a closed loop to 0.02 seconds, with a 56% increase in speed, achieving the expected goal. However, the overshoot of the output voltage waveform is quite large. In the future, it is planned to adopt the inner loop current and outer loop voltage method, and replace the high-frequency and low-loss MOSFET tubes for further exploration. Based on the current application status of buck circuits, future research should make breakthroughs in three dimensions: high frequency, intelligence and systematization. Integrate SiC devices to achieve nanosecond-level response; A perturbation feedforward immune mechanism is constructed through load prediction to pre-adjust the duty cycle before the voltage mutation occurs, thereby suppressing the component voltage drop within 1%. Dynamically optimize control parameters, predict device failure, and design an intelligent fault self-healing closed loop.

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