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Through-Type Teaching Design Based on a Buck Converter

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Abstract: The through-type teaching design based on Buck converter is proposed, which contains the basic operational principle, single voltage closed-loop control, the completion of prototype and the forward extensions. The network knowledge system is constructed flexibly based on the undergraduate courses, such as fundamentals of electric circuits, analog electronic technology, power electronics, principle of automatic control, switching power supply and so on. Therefore, the students' engineering practical abilities such as circuit design, software simulation, hardware development and comprehensive debugging are cultivated, thus the comprehensive skills of electrical major students are enhanced.

Keywords: Buck Converter; Through-Type Teaching Design; Closed-Loop Control; Software Simulation; hardware design

1. Introduction

DC regulated power supplies are widely used in industrial control, aerospace systems, communication base stations, embedded devices, and consumer electronics. Among different power supply forms, switching power supplies occupy a dominant position because they usually provide small size, low weight, high conversion efficiency, and low steady-state loss. They have largely replaced traditional linear regulated supplies in many applications and have become an important foundation of modern power electronic systems [1]. With the rapid development of microprocessors, communication chips, sensors, and portable intelligent devices, loads increasingly require high switching frequency, low output voltage, large output current, and fast dynamic response. These requirements place stricter demands on efficiency, power density, transient performance, and stability of power converters [2]. The step-down Buck converter is one of the most basic and representative switching power supply topologies. Its output voltage ripple, transient response, compensation design, and control strategy remain important topics in both engineering practice and academic research [3].

The Buck converter is especially suitable for a through-type teaching design because it is simple enough for beginners to understand, while it also contains rich theoretical and engineering content. At the circuit level, it includes switching devices, diode freewheeling, inductive energy storage, capacitive filtering, and load regulation. At the system level, it involves steady-state analysis, state-space modeling, small-signal linearization, frequency-domain compensation, pulse width modulation, and closed-loop stability. At the implementation level, it requires device selection, printed circuit board layout, soldering, measurement, and debugging. Therefore, the Buck converter can serve as a concrete engineering object that connects multiple undergraduate courses and helps students build an integrated understanding of electrical engineering knowledge.

Traditional undergraduate teaching often separates theoretical courses from practical training. Students learn circuit analysis in one semester, analog electronics in another semester, power electronics in a later stage, and automatic control theory in an independent course. Although each course has a clear internal logic, students may find it difficult to understand how the knowledge from different courses is combined in real engineering tasks. As a result, they can derive formulas or complete isolated experiments, but they may not be able to design and debug a working circuit system independently. A through-type teaching design tries to solve this problem by using one engineering object as the main thread across different learning stages. In this paper, the Buck converter serves as this organizing thread, and the teaching process extends from basic circuit understanding to closed-loop control and hardware realization.

In the first and second undergraduate years, the teaching focus is placed on the hardware foundation and intuitive understanding of energy conversion. Through prerequisite courses such as electric circuit analysis and analog electronic technology, students analyze the basic topology of the Buck converter, understand the physical process of inductor current rising and falling, and learn the voltage-current characteristics of main components [4,5]. At this stage, circuit simulation is introduced as an auxiliary tool. Students can observe switching waveforms, inductor current ripple, and output voltage ripple under different duty ratios. This visual process helps them build a direct understanding of how a switching power supply works, which is often more effective than purely abstract formula derivation for beginners.

In the third undergraduate year, the learning depth moves toward system modeling and closed-loop control. In the power electronics course, students systematically study power semiconductor devices, converter topologies, modulation methods, and control strategies [6]. When this content is combined with automatic control theory, the teaching focus shifts from open-loop topology analysis to closed-loop system design [7]. State-space averaging and small-signal modeling are introduced to describe the dynamic characteristics of switching converters. Students then learn how to use frequency-domain methods to design a voltage feedback loop, such as a Type-II or Type-III compensation network, and they verify loop gain, crossover frequency, and phase margin by advanced simulation software [8-10].

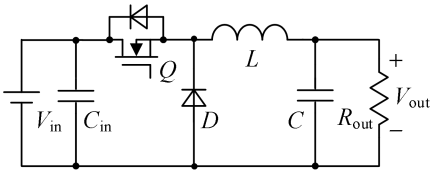
Theoretical analysis must be connected with hardware practice. In integrated electronic training, manufacturing practice, and related project courses, students are guided to move from theoretical design to physical circuit implementation. For example, mainstream high-speed synchronous Buck controller chips such as LM2727 and LM2737 can be introduced, and students are required to read English application materials, determine peripheral circuit parameters, design the feedback network, and prepare a practical debugging plan [11,12]. Through printed circuit board design, manual soldering, assembly, and hardware-software coordinated testing, students complete a key experimental closed loop. This process trains their ability to find and solve engineering problems, including waveform abnormality, layout interference, measurement error, oscillation, and thermal stress.

In the fourth undergraduate year, course design and graduation design can further extend the learning route to frontier topics. With the wide use of digital signal processors and microcontrollers, students can learn digital control algorithms and their implementation in modern switching converters [13,14]. They can also study how zero-voltage switching and other soft-switching methods reduce high-frequency switching loss and improve system efficiency [15,16]. For students with stronger research interest, the project can be extended to robust voltage regulation, nonlinear control, reinforcement learning control, maximum power point tracking, and stability problems under complex operating conditions [17]. In this way, the same Buck converter project continues to support progressive learning from basic concepts to advanced research.

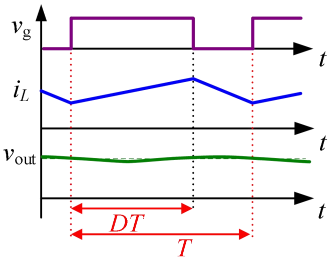
Based on the above teaching logic, this paper develops a complete through-type teaching design centered on the Buck converter. The design enables students to gradually master device selection, parameter calculation, small-signal modeling, loop compensation, simulation verification, hardware design, and system debugging. The teaching mode can be summarized as project-oriented, theory-sequential, and practice-integrated. It helps students form a structured network of knowledge rather than a fragmented collection of course points. It also supports the cultivation of high-quality applied engineering talents who can meet the needs of modern industry.

2. Basic Working Principle

The basic circuit of a Buck converter is shown in Figure 1(a). It consists of a switching device Q, a freewheeling diode D, a filter inductor L, and a filter capacitor C. In the ideal analysis, parasitic parameters are neglected. When the switch is turned on, the diode is reverse-biased and turned off. The input source, switch, inductor, output capacitor, and load form the main current path. The voltage across the inductor equals the difference between the input voltage and the output voltage, so the inductor current increases linearly. When the switch is turned off, the diode is forward-biased and conducts. The diode, inductor, output capacitor, and load form the freewheeling path. The inductor releases energy to the load and capacitor, and the inductor current decreases linearly. If the inductor current falls to zero, the converter enters discontinuous conduction mode and the output capacitor supplies the load energy [1,2].



(a) Buck Converter Circuit Topology



(b) Buck Converter Key Waveforms

Figure 1. Buck Converter Circuit Topology and Key Waveforms

When the circuit reaches steady state and operates in continuous conduction mode, the corresponding ideal waveforms are shown in Figure 1(b). Let the switching frequency be f, the switching period be T, and the duty ratio be D. If the capacitance is sufficiently large within one switching period, the output voltage ripple can be neglected and the output voltage is treated as a constant Vout. The rising and falling amplitudes of the inductor current can then be expressed as follows:

$$\Delta i_{L1}=\frac{(V_{in}-V_{out})DT}{L},\Delta i_{L2}=-\frac{V_{out}(1-D)T}{L} \tag{1}$$

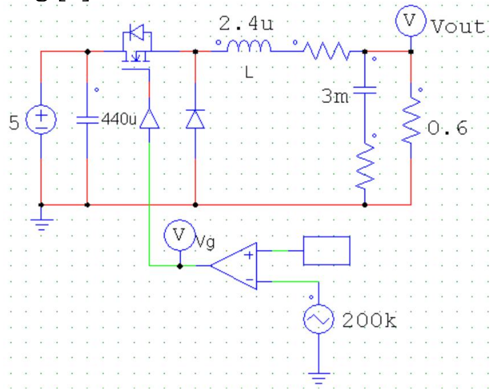
According to the volt-second balance of the inductor in steady state, the average voltage across the inductor over one switching period is zero. Therefore, the ideal voltage conversion ratio of the Buck converter is obtained as follows:

$$M=\frac{V_{out}}{V_{in}}=D \tag{2}$$

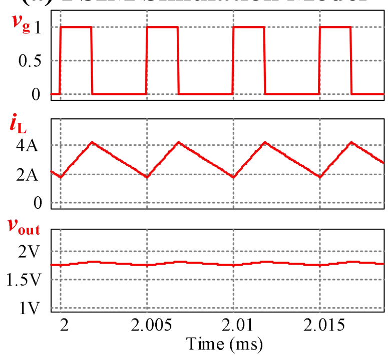
The capacitor voltage ripple within one switching period can be estimated by the charge variation of the output capacitor. Under the triangular inductor current ripple approximation, the output voltage ripple is calculated as follows:

$$\Delta V_{out}=\frac{\Delta Q}{C}=\frac{1}{C}\frac{1}{2}\frac{\Delta I_L}{2}\frac{T}{2}=\frac{\Delta I_L T}{8C} \tag{3}$$

The above equations support the preliminary parameter design of a Buck converter. The duty ratio can be calculated from the input and output voltage requirements. The switching frequency can then be selected according to efficiency, size, electromagnetic interference, and device constraints. The inductor value is determined from the allowed inductor current ripple, while the output capacitor value is selected from the required output voltage ripple. This process enables students to link physical waveforms with mathematical formulas and component selection, which is important for early-stage engineering training [3].



(a) PSIM Simulation Model



(b) Simulation Result

Figure 2. Open-Loop Switching Simulation of the Buck Converter

At the basic stage, simulation software can be used to deepen students' understanding of the operating principle. Common circuit and power electronics simulation tools include Multisim, PSPICE, Saber, SIMPLIS, MATLAB/Simulink, and PSIM. PSIM, which stands for Power Simulation, is a specialized simulation tool for power electronics and motor control. It provides fast simulation speed, relatively easy convergence, and a friendly interface. In this teaching design, PSIM is used to simulate the Buck converter under open-loop conditions. The simulation model is shown in Figure 2(a). The main parameters are set as follows: the input voltage is 5 V, the output voltage is 1.8 V, the input filter capacitance is 440 μF, the inductor is 2.4 μH, the output capacitance is 3000 μF, the switching frequency is 200 kHz, and the output current is 3 A. Because the inductor and capacitor may produce resonance and low-frequency oscillation, an appropriate equivalent series resistance is added for damping. The steady-state waveforms are shown in Figure 2(b).

From a teaching perspective, this simulation step has two functions. First, it gives students a visual representation of the switching node voltage, inductor current, and output voltage. Second, it allows students to change the duty ratio, inductance, capacitance, switching frequency, and load, and then observe how these parameters influence ripple and transient response. This interactive process makes the abstract design equations more concrete and prepares students for later closed-loop control design.

3. Voltage Closed-Loop Control Design

After students understand the basic working principle, the next step is to design the closed-loop control system. The design procedure includes determining the transfer function of the main power stage, drawing the system block diagram, selecting the desired crossover frequency and compensator type, calculating compensator parameters, deriving the total open-loop transfer function, obtaining the theoretical crossover frequency and phase margin, and verifying the result through closed-loop simulation. This section uses voltage-mode control as the main teaching example because it is intuitive and closely connected with automatic control theory.

3.1 AC Small-Signal Model of the Buck Power Stage

The AC small-signal modeling method is used to derive the transfer function of the Buck power stage [4,5]. During modeling, the equivalent series resistance of the inductor and capacitor affects the pole-zero locations of the transfer function. Therefore, the Buck power stage is redrawn with parasitic parameters, as shown in Figure 3. This model helps students understand why ideal circuit equations are not sufficient for dynamic design and why parasitic parameters must be considered in engineering implementation.

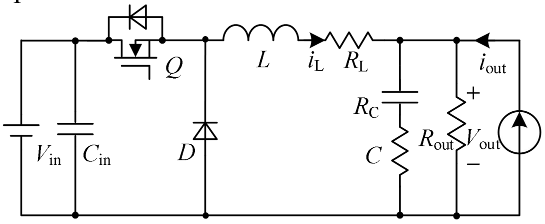


Figure 3. Buck Power Stage Topology with Equivalent Series Resistance

The state equations are first written separately for the two switching intervals. When the switch is on, the inductor is charged by the input source. When the switch is off, the inductor releases energy through the freewheeling path. The state equations can be expressed as follows:

$$\begin{cases} L\frac{di_L}{dt}=V_{in}-V_{out}-i_L R_L \\ C\frac{dv_C}{dt}=i_L-\frac{V_{out}}{R_{out}}=V_{out}-v_C \end{cases},0<t<DT$$
$$\begin{cases} L\frac{di_L}{dt}=V_{in}-V_{out}-i_L R_L \\ C\frac{dv_C}{dt}=i_L-\frac{V_{out}}{R_{out}}=V_{out}-v_C \end{cases},DT<t<T \quad (4)$$

When the converter satisfies the low-frequency assumption and the small-ripple assumption, the static operating point of the converter satisfies the following averaged equations:

$$\begin{cases} L\frac{di_L}{dt}=DV_{in}-V_{out}-i_L R_L \\ C\frac{dv_C}{dt}=i_L-\frac{V_{out}}{R_{out}}=V_{out}-v_C \end{cases} \quad (5)$$

Solving the static operating point gives the steady-state inductor current and voltage conversion relationship:

$$\begin{cases} I_L=\frac{V_{out}}{R_{out}} \\ \frac{V_{out}}{V_{in}}=\frac{DR_{out}}{R_{out}+R_L}\approx D \end{cases} \quad (6)$$

After linearization, this steady-state result is consistent with the ideal calculation result in equation (2) when parasitic resistance is small. The next step is to apply AC perturbations and separate the perturbation terms. The small-signal state equations can be written as follows:

$$\begin{cases} sL\hat{i}_L=\hat{d}V_{in}+D\hat{v}_{in}-\hat{v}_{out}-\hat{i}_L R_L \\ sC\hat{v}_C=\hat{i}_L-\frac{\hat{v}_{out}}{R}+\hat{i}_{out} \\ \hat{v}_{out}-sC\hat{v}_C R_C=\hat{v}_C \end{cases} \quad (7)$$

Based on these equations, the standard small-signal equivalent circuit can be drawn, as shown in Figure 4. This circuit provides a bridge between circuit theory and control theory. Students can see that a power converter is not only a switching circuit but also a dynamic system with input perturbations, control perturbations, output perturbations, and load disturbances.

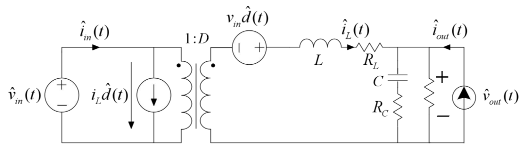


Figure 4. Small-Signal Equivalent Circuit of the Buck Converter

The transfer function from duty ratio to output voltage can then be obtained. Because RL and RC are much smaller than Rout, the linearized result is simplified as follows:

$$G_{vd}(s)=\left.\frac{\hat{v}_{out}}{\hat{d}}\right|_{\hat{v}_{in}=0,\hat{i}_{out}=0}\approx\frac{V_{in}(1+sCR_C)}{1+s\left[\frac{L}{R_{out}}+C(R_L+R_C)\right]+s^2LC} \quad (8)$$

The transfer function of the Buck power stage contains a double pole formed by the output filter inductor and capacitor and a zero formed by the equivalent series resistance of the output capacitor. After substituting the selected parameters, the LC double-pole frequency and the ESR zero frequency can be calculated as follows:

$$f_{P0}=\frac{1}{2\pi\sqrt{LC}}=\frac{1}{2\pi\sqrt{2.4\times10^{-6}\times3\times10^{-3}}}=1.876\times10^3 \quad (9)$$

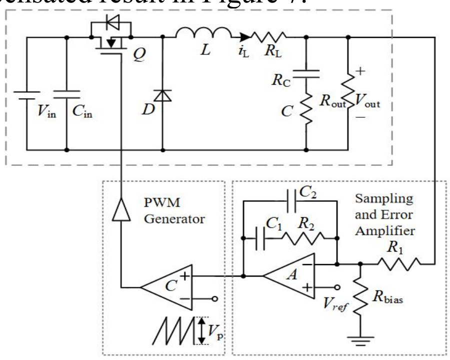
$$f_{Z0}=\frac{1}{2\pi CR_C}=\frac{1}{2\pi\times3\times10^{-3}\times29\times10^{-3}}=1.829\times10^3 \quad (10)$$

Because of the equivalent series resistance, the zero partly offsets the phase shift caused by the LC double pole, so the system can retain a certain phase margin near the crossover frequency. This point is valuable in teaching because it shows students that parasitic parameters are not always harmful. In some cases, they also change dynamic behavior in a way that can be used in control design.

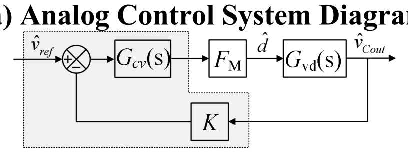
3.2 Voltage Closed-Loop Control Design

To eliminate static error and broaden the mid-frequency bandwidth, a closed-loop control loop must be designed [6]. A simple and commonly used control method for a DC regulated power supply is single-voltage closed-loop control. An analog-controlled Buck converter is shown in Figure 5(a), including the sampling circuit, error amplifier, and pulse width modulation generator. The extracted control block diagram is shown in Figure 5(b). In the feedback path, K denotes the feedback sampling coefficient. The difference between the reference value and the sampled feedback value produces the error signal. The error signal passes through the compensator Gcv(s), then is compared with the ramp carrier in the PWM generator to generate the duty-ratio signal. This signal is sent to the power stage Gvd(s), and the output voltage is obtained. The amplitude of the ramp carrier in the PWM generator is Vp. When the modulating signal reaches its maximum value, the duty ratio is 1, and therefore Fm=1/Vp.

Let Vp=2 V. For the PWM generator and power stage of the Buck converter, a single-zero double-pole compensator can be used. Its circuit and ideal Bode plot are shown in Figure 6. Before compensation, although the zero in the power-stage transfer function can partly compensate for the phase lag caused by the LC double pole, the low-frequency gain is still insufficient, the crossover frequency is low, and the response speed is limited. Therefore, a compensation network is necessary. According to automatic control theory, the compensated crossover frequency is usually selected at about one tenth of the switching frequency to obtain good dynamic response. The phase margin is usually selected within the range of 45° to 60° to meet stability requirements [7]. Different controlled objects have different amplitude-frequency characteristics, so an appropriate compensator type must be selected. The Bode plot of the uncompensated PWM generator and power stage is later compared with the compensated result in Figure 7.

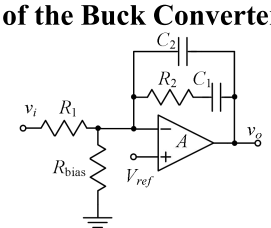


(a) Analog Control System Diagram

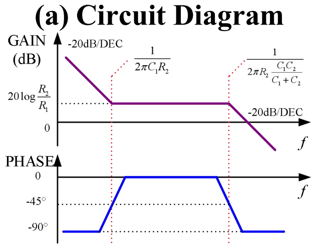


(b) Control Block Diagram

Figure 5. Single-Voltage Closed-Loop Control of the Buck Converter



(a) Circuit Diagram



(b) Bode Plot

Figure 6. Analog Compensator

The transfer function of the compensator is calculated as follows:

$$G(s)=KG_{cv}(s)=\frac{1+sR_2C_1}{sR_1(C_1+C_2)\left(1+sR_2\frac{C_1C_2}{C_1+C_2}\right)} \quad (11)$$

The corresponding zero, pole, and mid-frequency gain are expressed as follows:

$$AV=\frac{R_2}{R_1};\quad f_1=\frac{1}{2\pi R_2C_1};\quad f_2=\frac{C_1+C_2}{2\pi R_2C_1C_2}; \quad (12)$$

In this converter, Vref=0.6 V and Vout=1.8 V. If Rbias is selected as 1 kΩ, then R1 is selected as 2 kΩ. Combined with the transfer function of the power stage, the required zero and pole locations of the compensator can be determined. The expected compensated loop-gain crossover frequency is about one tenth of the switching frequency, namely 20 kHz, and the loop should cross the 0 dB axis with a slope of about -20 dB/dec. Therefore, the zero of the compensator is designed at half of the crossover frequency, f1=10 kHz, and the pole is placed at half of the switching frequency, fs/2=100 kHz. The gain of Gvd(s) at the crossover frequency is -12.313 dB, so R2 is calculated as follows:

$$R_2=R_1\times 10^{\frac{12.313}{20}}=8.254k\Omega \quad (13)$$

In practical design, R2 is selected as 8.2 kΩ. According to equation (12), C1=1.941 nF and C2=215.7 pF are obtained, and practical standard values C1=2.2 nF and C2=220 pF are selected. Mathcad is used to draw the theoretical Bode plot after compensation, as shown by the solid curve in Figure 7. The total open-loop transfer function, also called loop gain, is Tv(s)=G(s)FmGvd(s). After substituting the component values, the theoretical crossover frequency is 19.43 kHz, and the phase margin is 55.7°. After compensation, the dynamic performance and stability of the system satisfy the closed-loop design requirements.

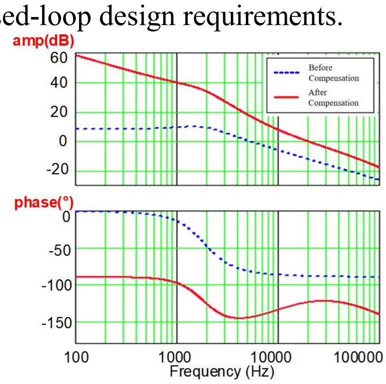
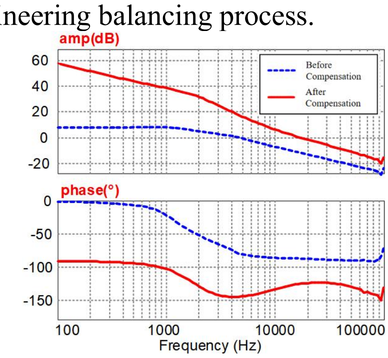


Figure 7. Bode Plots Before and After Compensation Drawn by Mathcad

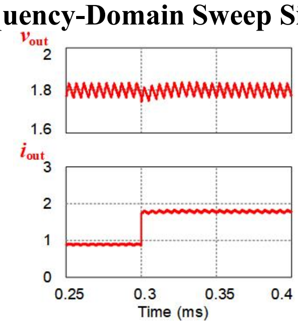
3.3 Closed-Loop Simulation

After the closed-loop parameters are designed, simulation software can be used to verify the transfer-function Bode plot. Common tools include Saber, SIMPLIS, MATLAB, and PSIM. This paper uses PSIM for verification. First, the uncompensated PWM generator and power stage are swept in the frequency domain, as shown by the dashed curve in Figure 8(a). Then, the loop gain after compensation is swept, as shown by the solid curve in Figure 8(a). The comparison between Figure 8(a) and Figure 7 shows that the simulation results are consistent with the theoretical design. This mutual verification is helpful for teaching because it makes students compare formula calculation, frequency-domain analysis, and simulation data in one design process.

On this basis, a time-domain load-step simulation is carried out. When the load steps from 30% of full load to 60% of full load, the output voltage maintains stability and recovers quickly, as shown in Figure 8(b). The time-domain response verifies that the designed compensation network provides acceptable voltage regulation performance. Students can also adjust the compensation parameters and observe the trade-off among response speed, overshoot, phase margin, and robustness. This exercise helps them understand that control design is not only a calculation problem but also an engineering balancing process.



(a) Frequency-Domain Sweep Simulation



(b) Time-Domain Simulation

Figure 8. PSIM Closed-Loop Simulation Results

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4. Hardware Circuit Design and Implementation

A traditional Buck converter contains one switch and one diode. If a switch is used to replace the diode, synchronous rectification is formed. This method reduces rectification loss and improves converter efficiency, especially in low-voltage and high-current applications. LM2727 and LM2737 are high-speed synchronous step-down regulator controller chips produced by TI. Their input voltage range is 2.2 V to 16 V, and the output voltage can be adjusted down to 0.6 V. The output current range can cover 0.7 A to 20 A in appropriate designs. The switching frequency can be adjusted from 50 kHz to 2 MHz by an external resistance Rf, and the efficiency can reach up to 95%. The chip integrates an oscillator, error amplifier, PWM comparator, synchronous driving logic, high-side and low-side MOSFET gate drivers, soft start, current limit, output overvoltage protection, and undervoltage protection circuits [8,9]. After theoretical parameter design and closed-loop control design, the hardware circuit is implemented by using the LM2737 controller to build an analog-controlled synchronous Buck converter.

4.1 Key Peripheral Circuits of the Analog Controller Chip

The simplified internal structure of the chip and the external key components are shown in Figure 9. The non-inverting terminal of the internal error amplifier is connected to a stable 0.6 V reference. The inverting terminal is connected to the FB pin, and the output terminal is connected to the EAO pin. By adding appropriate resistors and capacitors, the function of the analog compensator shown in Figure 6 can be realized. The ramp carrier varies from 1.25 V to 3.25 V, so the corresponding ramp amplitude is Vp=2 V. The generated PWM signal is amplified by the synchronous driving logic and then drives the MOSFETs. The high-side switch of the bridge arm uses a bootstrap supply formed by a diode and a capacitor. At the same time, peripheral circuits for voltage protection, current sensing, and frequency selection must also be designed. These circuits are not described in detail because the teaching focus is placed on the closed-loop design route and hardware debugging process.

4.2 Hardware Circuit Design and Experimental Results

Appropriate main power components are selected to build the hardware platform. The switching device is a TI CSD16414Q5 MOSFET. The inductor is implemented by connecting two Codaca CSEB1060 1.2 μH inductors in series. The input capacitor consists of two 220 μF capacitors in parallel, and the output capacitor consists of three 1000 μF capacitors in parallel. Students learn to use Altium Designer, KiCAD, Cadence Allegro, or similar tools to draw the printed circuit board, prepare the layout, manufacture the board, and solder the components. During debugging, they also learn to use basic instruments such as a multimeter, DC power supply, oscilloscope, and signal generator. Hardware debugging first ensures that the converter works normally under open-loop conditions, and then proceeds to closed-loop debugging.

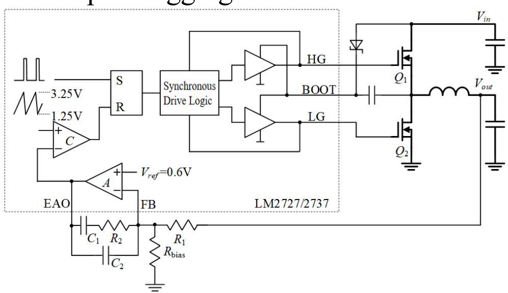
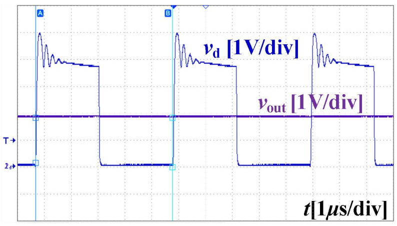
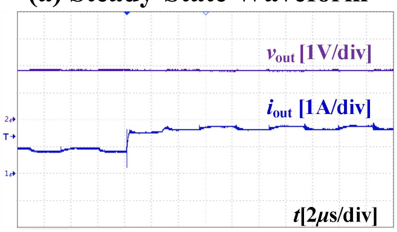


Figure 9. Simplified Electrical Connection of the LM2737 Controller



(a) Steady-State Waveform



(b) Load Step Waveform

Figure 10. Experimental Results

In the test platform, Rf is selected as 136 kΩ, and the switching frequency measured by the oscilloscope cursor is 196.1 kHz. Under steady-state conditions, the midpoint voltage waveform of the two switches, denoted as vd, and the output voltage waveform, denoted as vout, are shown in Figure 10(a). The output voltage measured by the multimeter is 1.788 V, indicating that stable voltage output is achieved. The load-step waveform is shown in Figure 10(b). Because of limited testing conditions, certain interference and measurement errors are introduced. Even so, when the load changes suddenly, the output voltage remains basically stable. This experimental result supports the effectiveness of the voltage closed-loop design and shows students the difference between ideal simulation and real hardware measurement.

The hardware stage is the most important part of the through-type teaching design because it exposes students to practical uncertainties that cannot be fully covered by theory. For example, the parasitic inductance of PCB traces may cause voltage spikes; poor grounding may introduce switching noise into the feedback signal; the equivalent series resistance of the capacitor may affect ripple and stability; and the measurement probe itself may influence high-frequency waveform observation. These problems require students to connect circuit theory, device knowledge, control analysis, and experimental skills. In this way, the project trains both analytical ability and practical judgment.

5. Conclusion

The Buck converter is widely used and has a relatively basic working principle, so it is suitable as an introductory yet expandable engineering object. By integrating it into a through-type teaching design across the undergraduate stage, students can develop related professional knowledge and engineering ability in a progressive manner. The design connects electric circuit analysis, analog electronics, power electronics, automatic control, switching power supply design, software simulation, and hardware debugging. It enables flexible use and cross-integration of multiple course theories and systematically improves students' engineering practice abilities, including circuit design, simulation analysis, hardware development, instrument operation, and comprehensive debugging.

The teaching route also improves students' learning motivation and self-learning ability. When students see that formulas, simulations, printed circuit boards, and oscilloscope waveforms all describe the same physical system, their understanding becomes more integrated. They are no longer limited to isolated knowledge points, but can form a complete view of the power electronics direction. Because of space limitations, this paper only briefly introduces the extension directions, including digital control, soft switching, high-efficiency conversion, and advanced robust control. These directions can guide students to carry out innovative research and improve their abilities in technical documentation and oral presentation. The proposed teaching design conforms to the spiral learning law and meets the demand for comprehensive engineering skills under the background of emerging engineering education. It is worthy of practical implementation and further analysis.

Acknowledgments

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