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Constant Current Control of DC Electronic Load based on Boost Topology

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***Abstract*—DC electronic load has a relatively wide range of applications to test and evaluate the steady-state and transient response characteristics of emerging power sources. In this paper, a DC electronic load operating in constant current mode is presented. This device is designed based on Boost topology and can achieve high control accuracy. The experimental results show that the proposed electronic load has high precision and power scalability relative to the traditional resistive load.**

***Index Terms*—DC electronic load, constant current, pulse width modulation, load regulation.**

I. INTRODUCTION

DC loads are usually used by power source developers and customers to test and evaluate the steady-state and transient response characteristics of emerging power sources [1], [2]. For example, the usual way to acquire discharging response and polarization curves of battery is through association of many power resistors. Such type of testing arrangement is characterized by a stiff and heavy operation with high power losses and large volumes. And nowadays this conventional test method has been replaced with the wide application of DC electronic loads.

The literature about DC electronic loads is limited to use a transistor (usually a MOSFET) as load [3], [4]; the resistance between drain and source is modulated through the gate-source voltage. The MOSFET in this method operates in three operation modes (cut-off, active and ohmic region). As a result, most of the power delivered by the source has to be dissipated by this device, which limits its application.

For the convenience of power expansion and control accuracy, PWM (Pulse Width Modulation) switching circuit topology (usually DC-DC converter) was proposed to implement DC electronic load in this paper. Such converters can be directly controlled by computers or implemented by automated controllers to simulate DC real loads at desired current or voltage levels. Furthermore, since the power device works in the switching state and the heating is small, a higher efficiency can be achieved.

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Usually DC electronic load can operate in four modes: constant current mode (CC mode), constant voltage mode (CV mode), constant resistance mode (CR mode) and constant power mode (CP mode) [4]. In this paper we pay attention to the realization of constant current mode. Constant current electronic load is a power supply provided on a constant current value to simulate or replace the real, static load, which is less affected by the environment factor.

This paper proposes the use of a Boost DC-DC converter as a variable electronic load to obtain constant current characteristics. Such configuration reduces the input current ripple and improves the steady-state accuracy. In addition, a classical control technique shown in Section III is used to ensure a stable operation of the converter. Experiment results shown in Section IV confirm the effectiveness of the proposed electronic load as a very useful tool to characterize the performance of under test power supply or battery.

II. SCHEME OF DC ELECTRONIC LOAD

Fig. 1 presents three basic topologies of DC-DC converters (Buck, Boost and Buck-Boost (Cuk)), which can be controlled electronically by changing the duty cycle of the converter in the range [0, 1]:

1) Buck topology is shown in Fig. 1(a). Buck circuit structure is simple and the use of PWM control mode can regulate the level of the output voltage and current easily. Due to the cyclical nature of the power device, the current of input port is discontinuous, which would cause high input current ripple. This feature makes Buck chopper difficult in the application of constant current control;

2) Boost topology is shown in Fig. 1(b). Boost chopper circuit is similar to the structure of Buck chopper, and the working state is also simple and easy to analyse. The inductance of Boost chopper is at the input, as long as the inductance value is greater than the critical value, the chopper would work in Continuous Conduction Mode (CCM) and the input current keeps continuous. This feature makes Boost topology a viable option for constant current control;

3) Cuk topology is shown in Fig. 1(c). There is a little difference with Buck and Boost circuit structure. The current of Cuk topology in input and output port is continuous, which also is a viable structure for constant current control. However, compared with Buck and Boost structure, its

working mode and circuit parameter design is relatively complex.

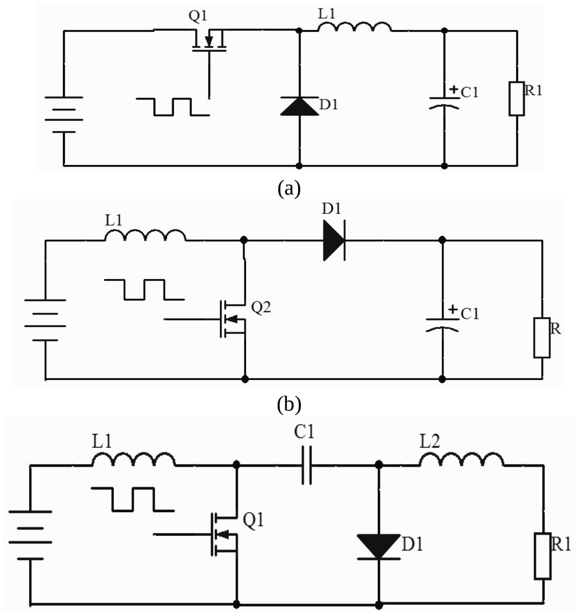


Fig. 1. DC power supply topology: (a) – buck chopper, (b) – boost chopper, (c) – cuk chopper.

Combination of above analysis, the structure of Boost circuit is simple and can ensure a continuous current in input port. Therefore, Boost topology was proposed to realize constant-current DC electronic load in this paper.

III. DESIGN OF DC ELECTRONIC LOAD

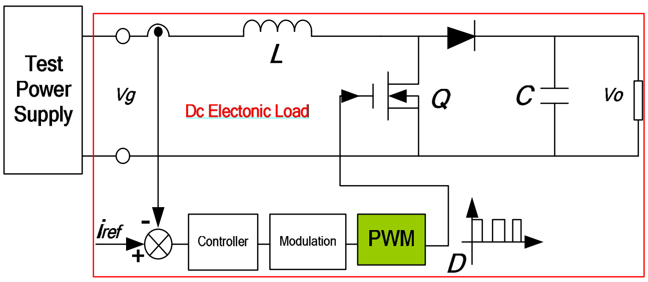


Fig. 2. Diagram of constant current control circuit.

The proposed DC electronic load is shown in Fig. 2, which includes constant current block. *Vg* is the input voltage. *Vo* is the output voltage. *Iref* is the input current command. *L* is the energy storage inductor. *C* is the filter capacitor. *Q* is the switching device (MOSFET). The duty cycle (*D*) in the range [0, 1] is the ratio of the time of conduction (*Ton*) to the switching period (*Ts*)

A. Design of Boost Inductance

In order to improve the efficiency and control accuracy of constant current, the system should operate in a continuous state. So the inductance value should be designed firstly. By the relations of inductance volt-second balance in one switching period [5], (1) and (2) can be obtained

$$\frac{V_g * D * T_S}{L} = \frac{(V_o - V_g) * (1-D) * T_S}{L}, \tag{1}$$

$$\Rightarrow D = 1 - \frac{V_g}{V_o}. \tag{2}$$

According to energy conservation, $V_g * I_{mid} * T_s = V_o * I_o * T_s$ can be obtained. I_{mid} is central value of CCM Boost inductor current

$$\Rightarrow I_{mid} = \frac{V_o * I_o}{V_g} = \frac{I_o}{1-D}. \tag{3}$$

Considering the output minimum load $I_{o\min}$ and $\Delta I = 2I_{mid}$, (4) can be shown as follows. Thus the critical inductance value can be achieved as (5):

$$\Rightarrow \frac{V_g * D * T}{2L} = \frac{I_{o\min}}{1-D}, \tag{4}$$

$$\Rightarrow L = \frac{V_o * (1-D)^2 * D}{2 I_{o\min} * f}. \tag{5}$$

As long as the design value of inductance is greater than the critical value, the input current can be continuous.

B. Design of Controller

In order to ensure the system achieves good control performance, mathematical modeling should be obtained before controller design.

1) Modeling

State average method is used to obtain the mathematical model of the Boost circuit [6], [7]. Firstly, an operation should be done to the voltage or current variable within a switching cycle average and the equivalent average parameter got. Thereby the impact of switching corrugation can be eliminated. Then, the average variable is expressed as the summation of AC component and DC component (such as, input voltage $V_g + \hat{v}_g(t)$, input inductor current $I + \hat{i}(t)$, output capacitor voltage $V_o + \hat{v}_o(t)$), and a small signal component ($\hat{v}_g(t)$, $\hat{i}(t)$, $\hat{v}_o(t)$, $\hat{d}(t)$) can be obtained after elimination of the DC component to achieve the purpose of the separation of small signal. Finally, linear processing is done to these small signal components. The nonlinear system is approximated as a linear system in the vicinity of the DC operating point, and thus each kind of methods for circuit analysis and design can be applied to this system.

According to the above described method, small signal model of Boost circuit can be shown in Fig. 3.

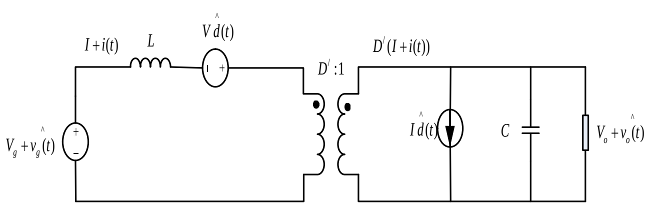


Fig. 3. Small signal model of Boost topology.

Small signal state average equation can be written as follows

$$\begin{bmatrix} \dot{i} \\ \dot{v}_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1-d_0}{L} \\ \frac{1-d_0}{C} & -\frac{1}{RC} \end{bmatrix} \bullet \begin{bmatrix} i \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \bullet v_g + \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & 0 \end{bmatrix} \hat{d}, \quad (6)$$

Based on (6), the transfer function of Duty cycle $\hat{d}$ to output voltage $\hat{v}_o$ and input inductance current $\hat{i}$ can be achieved as (7) and (8):

$$G_v(s) = \frac{\hat{v}_o}{\hat{d}} = \frac{-sLi_{L0} + (1-d_0)u_{c0}}{LCs^2 + sL/R + (1-d_0)^2}, \quad (7)$$

$$G_i(s) = \frac{\hat{i}}{\hat{d}} = \frac{(1-d_0)i_{L0} + (sC + 1/R)u_{c0}}{LCs^2 + sL/R + (1-d_0)^2}. \quad (8)$$

2) Design of Control Parameter

The control block in Fig. 2 can be equivalent to Fig. 4. The control target is to keep the input current to be constant. The system adopted digital control. Digital control has strong anti-jamming capability, noise margin, easy to implement complex algorithms, reprogrammable advantages [8], [9].

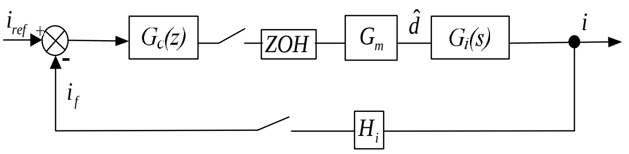


Fig. 4. Constant current diagram.

Here H_i is the coefficient of feedback current, i_{ref} is a given reference current, i_f is the feedback current. The modulator transfer function is

$$G_m(s) = \frac{\hat{d}(s)}{\hat{v}_c(s)} = \frac{1}{V_m}. \quad (9)$$

Classic PI controller has been adopted in this system. The discretization of PI controller can be got by bilinear transform $s = \frac{2}{T} \cdot \frac{1-z^{-1}}{1+z^{-1}}$

$$G_c(z) = k_p + \frac{k_i z}{z-1}. \quad (10)$$

Open-loop current transfer function of the system can be written as

$$G_{open}(z) = \overbrace{(k_p + \frac{k_i z}{z-1})}^{PIcontroller} \bullet H_i \bullet ZOH \bullet \overbrace{\frac{1}{V_P}}^{PWM} \bullet G_i(z). \quad (11)$$

Fig. 5 shows the Bode plot of open-loop current transfer function of the system.

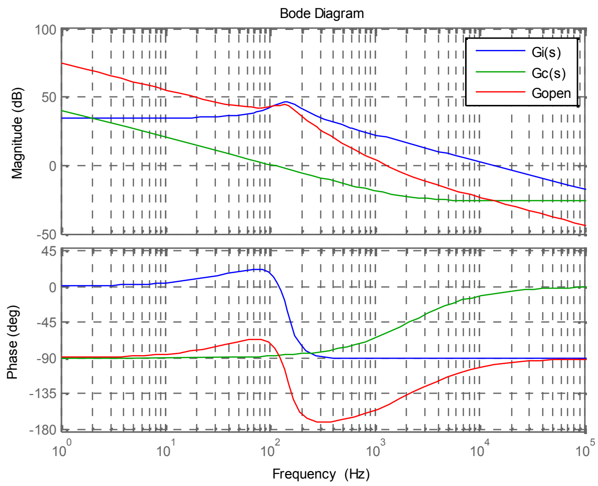
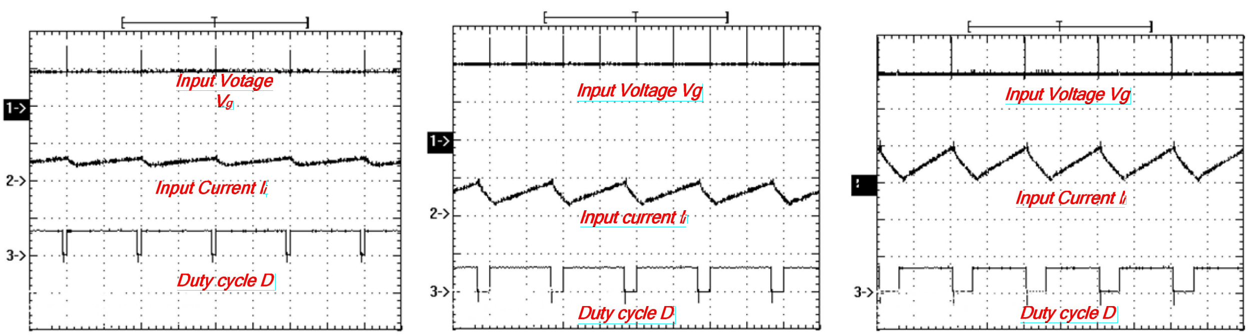


Fig. 5. Bode plot of open loop system.

As can be seen from Fig. 5, before correction the amplitude margin of open-loop control system is lower, and the cut-off frequency is 15 kHz. So system filtering performance to high frequency is poor and such a low amplitude margin cannot ensure high steady performance. Through a correction with PI controller, the slope of the corrected system is -20 dB/dec through 0 dB lines. So there will be a better phase stability and higher low frequency gain can be achieved. The cutoff frequency after the correction is 1.5 kHz. The correction reduced the high frequency switching ripple and improved the steady-state performance.



(a) (b) (c)

Fig. 6. Constant current control waveform under different voltage – Y(Chanel 1:5 V/div, Chanel 2:1 A/div, Chanel 3:20 V/div),X(100 ms/div), (a) input voltage Vg = 5 V, (b) input voltage Vg = 10 V, (c) input voltage Vg = 15 V.

IV. EXPERIMENT RESULTS

During performance tests, electronic load can be used for current source based controls, with programmable variation of the input current through digital variation of the reference current. To verify the working principle, a low power constant current electronic load based on Boost topology was designed in a laboratory. Setting range of the current is 100 mA–1000 mA. The input voltage range is 5 V–18 V and the rated input voltage is 10 V.

A. Verification of Constant Current

The experiment waveform is shown in Fig. 6 under different input voltage (5 V, 10 V, 15 V). CH1 is the input voltage waveform. CH2 is the input current waveform. CH3 is the duty cycle waveform. Seen from the Fig. 6, when the input voltage changes from 5 V to 15 V, the duty cycle decreases and the rate of change of the inductor current ΔI increases, but the DC average value of input inductance current remains unchanged. It shows that the better performance of the constant current control has been achieved.

B. Test Results

The experiments have been done from the accuracy of the steady, voltage regulation, load regulation.

1) Steady Accuracy

TABLE I. STEADY ACCURACY.

Reference Current	Input current (mA)	Error
0	0	0
100 mA	100	0
200 mA	199	0.50 %
300 mA	302	0.67 %
400 mA	401	0.50 %
500 mA	500	0
600 mA	601	0.50 %
700 mA	700	0
800 mA	801	0.50 %
900 mA	901	0.50 %
1000 mA	1001	0.50 %

Steady accuracy under different current level (0 mA–1000 mA) is shown in Table I when the input voltage is rated value 10V.

2) Voltage Regulation

The input current accuracy is shown in Table II when the input voltage of the electronic load changes from 6 V to 16 V.

TABLE II. VOLTAGE REGULATION.

Reference Current	Input current (mA)	Error
0	0	0
100 mA	93	5 %
200 mA	201	0.50 %
300 mA	295	1.60 %
400 mA	396	1 %
500 mA	498	0.40 %
600 mA	599	0.10 %
700 mA	701	0.14 %
800 mA	799	0.13 %
900 mA	907	0.78 %
1000 mA	1004	0.40 %

3) Load Regulation

Test diagram of load regulation is shown in Fig. 7. In order to facilitate the measurement of load regulation, a resistor *Rw* has been connected in series to the output end of the DC power supply under test. Load regulation can be calculated by different resistance *Rw*.

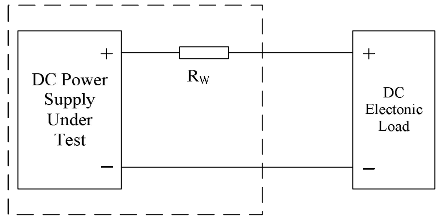


Fig. 7. Test diagram of Power load regulation.

The experiment result of Load regulation is shown as Table III.

TABLE III. LOAD REGULATION.

Value	Load regulation
Rw=1 Ω	0.13 %
Rw=0.5 Ω	0.56 %

V. CONCLUSIONS

A DC electronic load based on Boost topology has been designed to realize the function of constant current. The experiment results show that the current steady accuracy is high, which could meet the requirements of power supply under test. The test has been done in low power, the accuracy and stability would be higher when electronic load worked in high-power.

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