Compensation Design With TL431 for UCC28600

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Power Management/Field Application

ABSTRACT

TL431 is a 3-terminal, adjustable shunt regulator with precision programmable reference and good thermal stability. Because of low cost, excellent performance, and great thermal stability, TL431 has been widely used in all kinds of power supplies. UCC28600 is a quasi-resonant flyback green-mode controller with advanced energy-saving features; it is a hero product of TI and provides an excellent power-saving solution for power supplies. TL431 is adopted in UCC28600 circuit to make it stable and with a good load transient feature. This paper presents small signal modeling of DCM flyback. Due to circuit stability requirement, II order compensation network with TL431 is provided and parameters are calculated with stringent principle. Finally, experiment results verify that the theoretical analysis is correct.

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1. Introduction

UCC28600 is a quasi-resonant flyback controller with green-mode; it efficiently increases efficiency at light load. Flyback is an isolated topology, so optocoupler is required to isolate the feedback signal in feedback loop. Compared with most of amplifiers, TL431 is low cost and small. At the same time, TL4431 also has excellent performance and great thermal stability, thus it is widely used in various power supplies. In this paper, TL431 is adopted in UCC28600 flyback design.

2. Small Signal Model of DCM Flyback

Because UCC28600 is a quasi-resonant flyback, it operates in DCM mode; therefore, to design feedback network and calculate relevant parameter, small signal model of DCM flyback is needed.

The total small signal model is composed of the following functions:

- Duty production transfer function
- Filter circuit transfer function
- Compensation network transfer function

These transfer functions are discussed in the following sections.

2.1 Duty Production Transfer Function

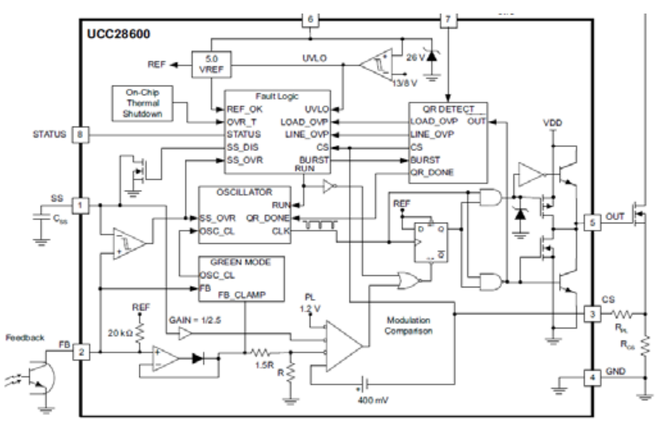

Figure 1. UCC28600 Block Diagram

Figure 1 is the UCC28600 block diagram, peak current mode (PCM) is observed in this figure. The FB pin of UCC28600 connects the collector of silicon NPN phototransistor. The voltage on the FB pin is called V_{comp}. V_{comp} goes through a voltage follower and a voltage divider, and then it compares with the sum of current sense voltage and 0.4 V. PWM is produced at the output pin of the comparator and drives the external MOSFET to switch. According to the theory of PCM, V_{comp} is equal to the sum of peak current sense voltage and 0.4 V [1]. Therefore, [There is a voltage drop in R_{pl} resistor, please count it in]

$$V_{comp} \times \frac{R}{R + 1.5R} = I_{peak} \times R_{cs} + 0.4 \tag{1}$$

It means,

$$0.4(V_{comp} - 1) = I_{peak} \times R_{cs} \tag{2}$$

Where I_{peak} is the peak current of MOSFET, R_{cs} is the current sense resistor.

Because the UCC28600 operates in DCM mode, current through MOSFET increases from zero at the beginning of the period, as described in Figure 2.

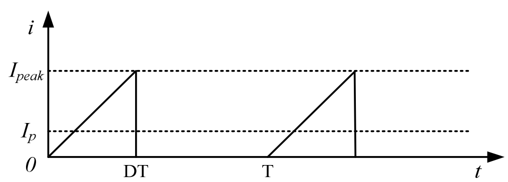

Figure 2. Current Through MOSFET Waveform

I_p is the average current of MOSFET, so the relationship between I_p and I_{peak} is:

$$I_p = \frac{\frac{1}{2} I_{peak} \times DT}{T} = \frac{1}{2} I_{peak} D \tag{3}$$

Where D is duty cycle. I_{peak} is obtained by Equation (3).

$$I_{peak} = \frac{2 I_p}{D} \tag{4}$$

UCC28600 operates in quasi-resonant mode, which is between real DCM and CCM mode. Because inductor current only reverses slightly in every period when the load is larger than approximately 30 percent full load, CCM gain formula can be used to obtain duty.

$$M = \frac{V_o}{V_{in}} = \frac{D}{n(1 - D)} \tag{5}$$

D is obtained by Equation (5).

$$D = \frac{nV_o}{V_{in} + nV_o} \tag{6}$$

At the specified state, V_{in}, V_o and n do not vary, so D is a constant parameter.

Equation (4) is put into Equation (2),

$$0.4(V_{comp} - 1) = \frac{2I_p}{D} \times R_{cs} \tag{7}$$

Assume the flyback transformer has no power loss, according to power conservation:

$$I_s = nI_p \tag{8}$$

Equation (8) is put into Equation (7),

$$0.4(V_{comp} - 1) = \frac{2I_s}{n \times D} \times R_{cs} \tag{9}$$

Differentiate at both sides of Equation (9),

$$0.4\frac{\mathrm{d}v_{comp}}{\mathrm{d}t} = \frac{2R_{cs}}{n \times D}\frac{\mathrm{d}i_s}{\mathrm{d}t} \tag{10}$$

Take Laplace transform at Equation (10),

$$\frac{v_{comp}(s)}{i_s(s)} = \frac{5R_{cs}}{n \times D} \tag{11}$$

Equation (11) is the duty production transfer function.

2.2 Filter Circuit Transfer Function

Figure 3 shows the filter circuit of UCC28600: C_{o1} and C_{o2} are filter capacitors; R_{o1} and R_{o2} are equivalent series resistances (ESR) of filter capacitors, respectively; L_o is filter inductance; and R_L is load resistance. Output voltage sample network is composed of R_1 and R_{lower}, which are parallel with R_L. R_d is defined as:

$$R_d = R_L // (R_1 + R_{lower}) \tag{12}$$

The reality is $(R_1 + R_{lower}) >> R_L$, so Equation (13) is adopted.

$$R_d \approx R_L \tag{13}$$

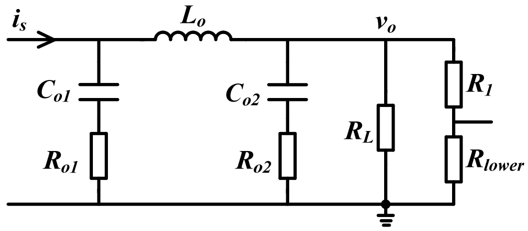

Figure 3. Filter Circuit

According to Figure 3, the filter circuit transfer function is stated as shown below:

$$\frac{v_o(s)}{i_s(s)} = \frac{R_{o1} + \frac{1}{sC_{o1}}}{R_d // (R_{o2} + \frac{1}{sC_{o2}}) + sL_o + R_{o1} + \frac{1}{sC_{o1}}} \times [R_d // (R_{o2} + \frac{1}{sC_{o2}})]$$

$$= \frac{(R_{o1} + \frac{1}{sC_{o1}}) \frac{R_d (R_{o2} + \frac{1}{sC_{o2}})}{R_d + R_{o2} + \frac{1}{sC_{o2}}}}{\frac{R_d (R_{o2} + \frac{1}{sC_{o2}})}{R_d + R_{o2} + \frac{1}{sC_{o2}}} + sL_o + R_{o1} + \frac{1}{sC_{o1}}} \tag{14}$$

Then, the original loop transfer function is deduced by Equations (11) and (14).

$$\frac{v_o(s)}{v_{comp}(s)} = \frac{v_o(s)}{i_s(s)} \times \frac{i_s(s)}{v_{comp}(s)} = \frac{nD}{5R_{cs}} \times \frac{(R_{o1} + \frac{1}{sC_{o1}}) \frac{R_d (R_{o2} + \frac{1}{sC_{o2}})}{R_d + R_{o2} + \frac{1}{sC_{o2}}}}{\frac{R_d (R_{o2} + \frac{1}{sC_{o2}})}{R_d + R_{o2} + \frac{1}{sC_{o2}}} + sL_o + R_{o1} + \frac{1}{sC_{o1}}} \tag{15}$$

2.3 Compensation Network Transfer Function

Flyback is a transformer isolation topology that can prevent high common voltage from transferring to output and keep personnel and devices safe. Thus, feedback circuit also must isolate. Optocoupler is adopted to achieve this function. TL431 is a 3-terminal adjustable shunt regulator that is similar, but not identical, to the amplifier. Figure 4 shows the typical application circuit of TL431.

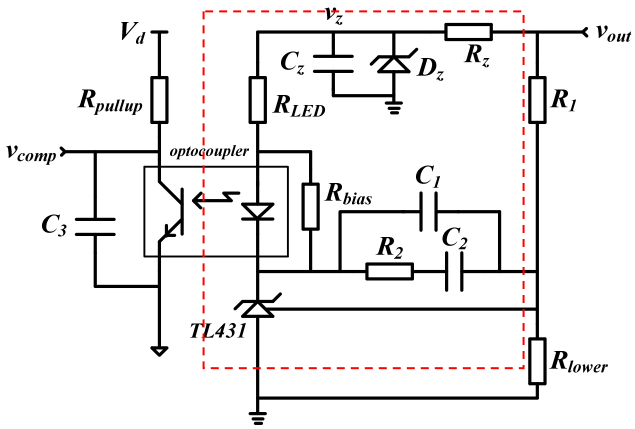

Figure 4. Compensation Network With TL431

In typical application circuit, the REF pin of TL431 connects the output of the V_{out} divider network and can sense the variation of V_{out}. The error signal is converted to sink current of the cathode pin, thus TL431 can be regarded as a transconductance amplifier [2].

If R_{LED} directly connects V_{out}, the ripple of V_{out} flows through R_{LED}. R_{LED} appears in the modulation channel and produces zero pole and polar pole, which influences system configuration. On the other hand, R_{LED} dominates the middle frequency gain of the feedback circuit. The limitation of the two aspects makes selection of R_{LED} complex and difficult [3]. Therefore, regulator network containing R_z, D_z, and C_z is introduced to set V_z constant, which releases R_{LED} from the modulation channel.

TL431 is regarded as a transconductance amplifier, so high transconductance gain is required in compensation application. A feature of TL431 is that when Ik that is the sink current of cathode pin keeps a low value, transconductance gain is low; however, when Ik rises, transconductance gain grows quickly, so the limitation of minimum Ik is set. The TL431 data sheet recommends a bias current of 1 mA. In Figure 4, R_{bias} provides the bias current.

Optocoupler is designed for signal transmission between two electrically separated circuits while maintaining a high degree of electrical isolation. IC/IF is called current transmission rate (CTR), which is related to IF and temperature. Generally, typical CTR value is adopted in analysis. C_{opto} is the equivalent capacitor that is parallel with the silicon NPN phototransistor. In Figure 4, C_3 is also parallel to C_{opto}, because C_{opto} is extremely smaller than C_3, so it is neglected in calculation.

To compensate original zero pole and polar pole to provide sufficient gain margin and phase margin, order II network is widely used. Order II network is composed of R_1, R_2, C_1, and C_2 in Figure 4. This order II network has one zero pole and two polar poles; it can offer sufficient DC gain, proper cross-over frequency, and excellent high-frequency attenuation.

As shown in paper [4], the transfer function of the part surrounded by a red dashed line in Figure 4 is:

$$\frac{v_{comp}(s)}{v_t(s)} = \left(\frac{1}{1+sR_{pullup}(C_3 // C_{opto})}\right)\frac{R_{pullup}}{R_{LED}}CTR \tag{16}$$

The transfer function of order II network is:

$$\frac{v_t(s)}{v_o(s)} = -\frac{(R_2+\frac{1}{sC_2})//\frac{1}{sC_1}}{R_1} = -\frac{sR_2C_2+1}{sR_1(C_1+C_2)(sR_2\frac{C_1C_2}{C_1+C_2}+1)} \tag{17}$$

Commonly, $C_2 >> C_1$, so Equation (17) can be simplified as shown below:

$$\frac{v_t(s)}{v_o(s)} = -\frac{sR_2C_2+1}{sR_1C_2(sR_2C_1+1)} \tag{18}$$

According to Equations (16) and (18), the compensation network transfer function can be deduced as follow:

$$\frac{v_{comp}(s)}{v_o(s)} = -\left(\frac{sR_2C_2+1}{sR_1C_2(sR_2C_1+1)}\right)\left(\frac{1}{1+sR_{pullup}(C_3 // C_{opto})}\right)\frac{R_{pullup}}{R_{LED}}CTR \tag{19}$$

3. Compensation Network Parameter Calculation

The 120-W UCC28600 evaluation module (EVM) is used to validate the theory; input DC voltage is from 120 to 410 V, output voltage is a constant value of 19.4 V, and rated power is up to 120 W.

The device value of the power circuit is provided in paper [5], $R_{cs} = 0.13\Omega$, $C_{o1} = 3600\mu F$, $R_{o1} = 8m\Omega$, $C_{o2} = 1800\mu F$, $R_{o1} = 16m\Omega$, $L_o = 4.7\mu H$, $R_d = 3.14\Omega$, $n = 6$.

The UCC28600 EVM is a wide-range input power module, as known to all, optimal compensation parameter of different condition is not the same. So 270 V is selected as a compromise. Then duty can be deduced by Equation (6), $D = \frac{nV_o}{V_{in}+nV_o} = 0.3$.

All of the preceding values are put in Equation (15). Actual original loop transfer function is achieved as shown in Equation (20).

$$\frac{v_o(s)}{v_{comp}(s)} = \frac{4.688\times10^{-9}s^2 + 3.256\times10^{-4}s + 5.652}{6.248\times10^{-11}s^3 + 3.29\times10^{-7}s^2 + 0.01106s + 0.65} \tag{20}$$

Figure 5 shows the Bode figure drawn by Matlab. Cross-over frequency is only 81.1 Hz, which is too low for UCC28600 and worsens the dynamic feature, because the minimum switch frequency of UCC28600 is 40 kHz. Generally, 1/5 to 1/10 of switch frequency is preferred as the cross-over frequency. However, in this circuit the loop cross-over frequency is designed between 2 and 3 kHz at nominal input voltage and 50 percent load with a phase margin of 70 to 80 percent, because the cross-over frequency varies 3-to-1 during its full range of operation [6]. As a result, 3 kHz is selected in calculation. The magnitude is –24 dB at 3 kHz in gain curve, so the compensation network should provide 24 dB to satisfy the requirement of cross-over frequency.

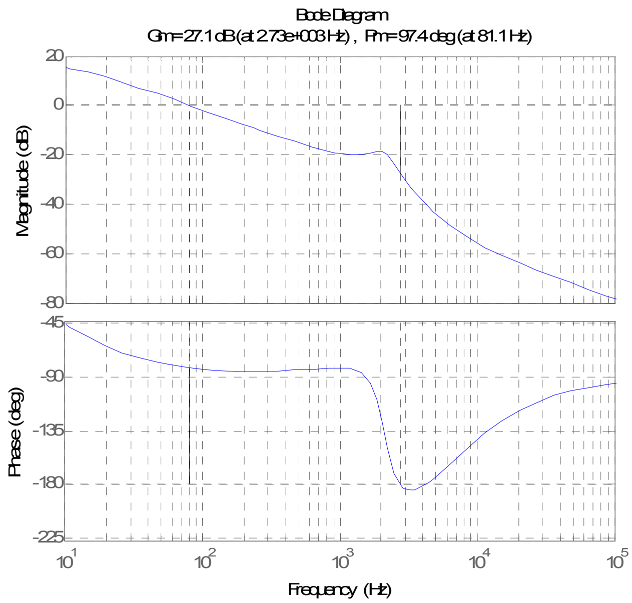

Figure 5. Bode Figure of Original Loop Transfer Function

According to compensation network and Equation (19), middle frequency gain of compensation network is as shown in Equation (21).

$$G_{mid} = \frac{R_2}{R_1} \frac{R_{pullup}}{R_{LED}} CTR \tag{21}$$

CNY17-1 is chosen as optocoupler and the typical forward voltage of its diode is 1.2 V, thus 1 kΩ is set as the value of R_{bias} to provide a bias current of 1 mA. I_F is the primary current of optocoupler and I_C is secondary current; I_F and I_C satisfy Equation (22). I_C is reflected to primary and flow through R_{LED}. R_{LED} is limited because if voltage dropout of R_{LED} is too high, the rest of the voltage cannot satisfy the operation requirement of TL431 [4]. So R_{LED} must comply with Equation (23). Another limitation concerns the TL431 middle frequency gain, shown as Equation (21); a large value of R_{LED} makes R_2 too large, thus weakening the signal dynamic feature. So the R_{LED} value is set as 499 Ω.

$$I_C = I_F \cdot CTR \tag{22}$$

$$R_{LED,\max} \le \frac{V_{out} - V_f - V_{TL431,\min}}{V_{dd} - V_{CE,sat} + I_{bias} CTR_{\min} R_{pullup}}$$

$$\le \frac{10 - 1.2 - 2.5}{5 - 0.3 + 1 \times 10^{-3} \times 0.3 \times 20 \times 10^3} \times 0.3 \times 20 \times 10^3 \le 3.5\text{k}\Omega \tag{23}$$

R_1 and R_{lower} are used to provide the reference voltage 2.5 V of TL431. Output voltage of UCC28600 is 19.4 V, so that 28 kΩ and 4.12 kΩ are chosen as the values of R_1 and R_{lower} , respectively.

According to the previous analysis, 24 dB magnitudes should be provided, so that 36.5 kΩ is selected as the value of R2.

$$R_2 = \frac{G_{mid} R_1 R_{LED}}{R_{pullup} CTR} = \frac{10^{\frac{24}{20}} \times 28 \times 10^3 \times 499}{20 \times 10^3 \times 0.3} = 36.9\text{k}\Omega \tag{24}$$

According to Equation (20), a low-frequency polar pole of 58.87 Hz exists. The zero pole of compensation network is designed to compensate it. Generally, polar pole is set at switch frequency or lower than switch frequency to attenuate high-frequency noise. Zero pole and polar pole can be achieved by Equation (19) and is as shown below.

$$f_z = \frac{1}{2\pi R_2 C_2} \tag{25}$$

$$f_{p1} = \frac{1}{2\pi R_2 C_1} \tag{26}$$

$$f_{p2} = \frac{1}{2\pi R_{pullup} C_3} \tag{27}$$

The values of C_1, C_2, and C_3 are obtained from below. C_1, C_2, and C_3 are set to 130 pF, 100 nF, and 200 pF, respectively.

$$C_2 = \frac{1}{2\pi R_2 f_z} = \frac{1}{2\pi \times 36.5 \times 10^3 \times 58.87} = 74nF \tag{28}$$

$$C_1 = \frac{1}{2\pi R_2 f_{p1}} = \frac{1}{2\pi \times 36.5 \times 10^3 \times 40 \times 10^3} = 109\,pF \tag{29}$$

$$C_3 = \frac{1}{2\pi R_{pullup} f_{p2}} = \frac{1}{2\pi \times 20 \times 10^3 \times 40 \times 10^3} = 199\,pF \tag{30}$$

4. Experiment

A 120-W UCC28600 EVM is used to certify the theory analysis and that all device values are set as above. Figure 6 is a Bode figure of a closed loop at 300 V input and full load. Cross-over frequency is 3.8 kHz and phase margin is 63 degrees, which satisfy the requirement of stable operation. Figure 7, Figure 8, and Figure 9 are output voltage waveforms at 300 V input and full load, half load, and no load, respectively. Output is a stable 19.4 V DC voltage, which indicates that compensation designed is proper and makes system accurate and stable at full range. Figure 10, Figure 11, and Figure 12 are output voltage ripple waveforms at 300 V input and full load, half load, and no load, respectively. Peak-to-peak voltage is 45 mV at full and half load, which is 0.23 percent of output voltage. When operating at no load, UCC28600 enters green mode, so output voltage ripple is as shown in Figure 12; peak-to-peak voltage is 60 mV. Figure 13 is an output load transient waveform from 10 to 90 percent load step change at 300-V input; overshoot voltage is 200 mV and adjust time is 2.5 ms, which demonstrates the system has an excellent load transient feature.

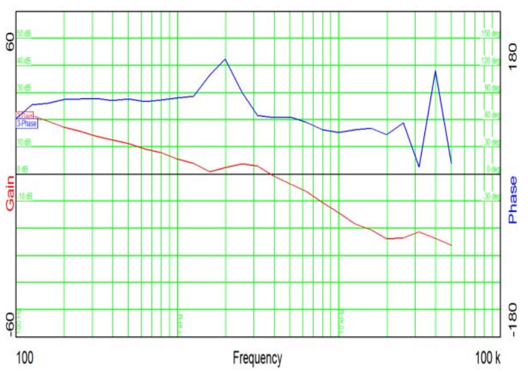

Figure 6. Bode Figure of Closed Loop

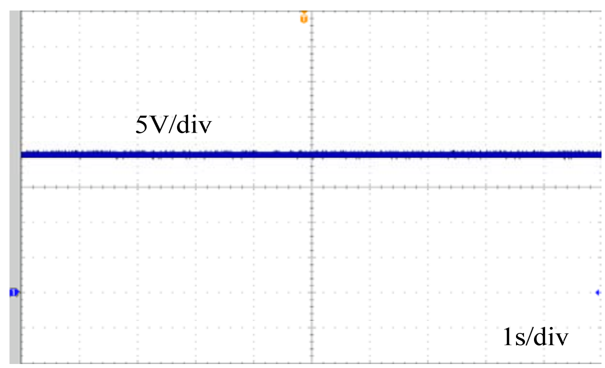

Figure 7. Output at 300-V Input, Full Load

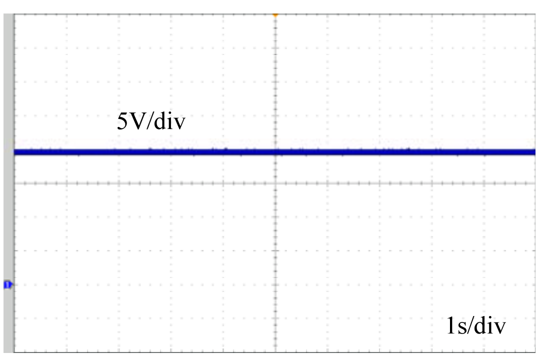

Figure 8. Output at 300-V Input, Half Load

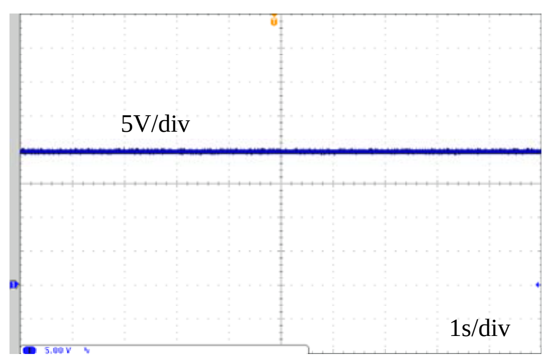

Figure 9. Output at 300-V Input, No Load

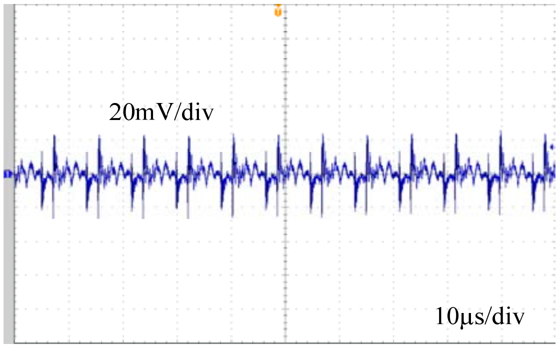

Figure 10. Output Ripple at 300-V Input, Full Load

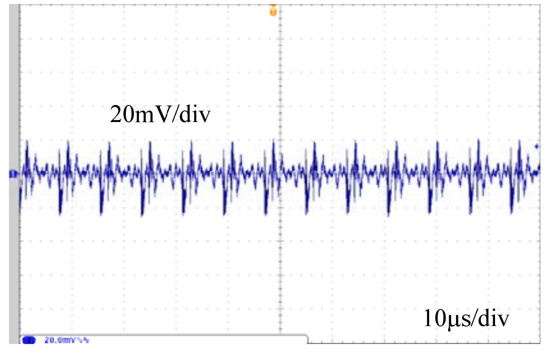

Figure 11. Output Ripple at 300-V Input, Half Load

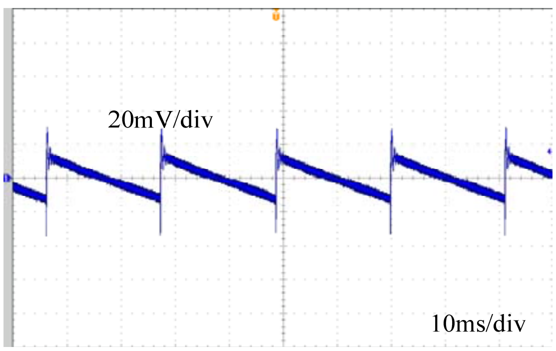

Figure 12. Output Ripple at 300-V Input, No Load

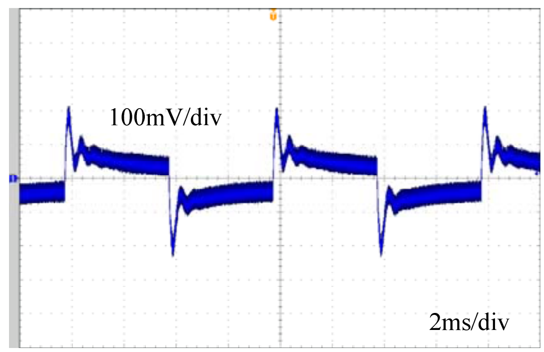

Figure 13. Output Load Transient at 300-V Input

5. Conclusion

TL431 is suitable for power supply design, and it is excellent, inexpensive, and small. Compensation network presented in this paper is certified proper and effective for UCC28600. Experiment results verify that the theoretical analysis is correct.

6. References

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