

# Design of a TL431-Based Controller for a Flyback Converter

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## 1 Introduction

The TL431 is a reference voltage source that is commonly used in the control circuit of isolated power supplies. Typically used to provide a precision reference voltage, the TL431 can also be configured as an analog controller by exploiting its on-board error amplifier. In this report, the design of a TL431-based voltage controller for a flyback converter is presented. The example circuit is shown in Fig. 1.

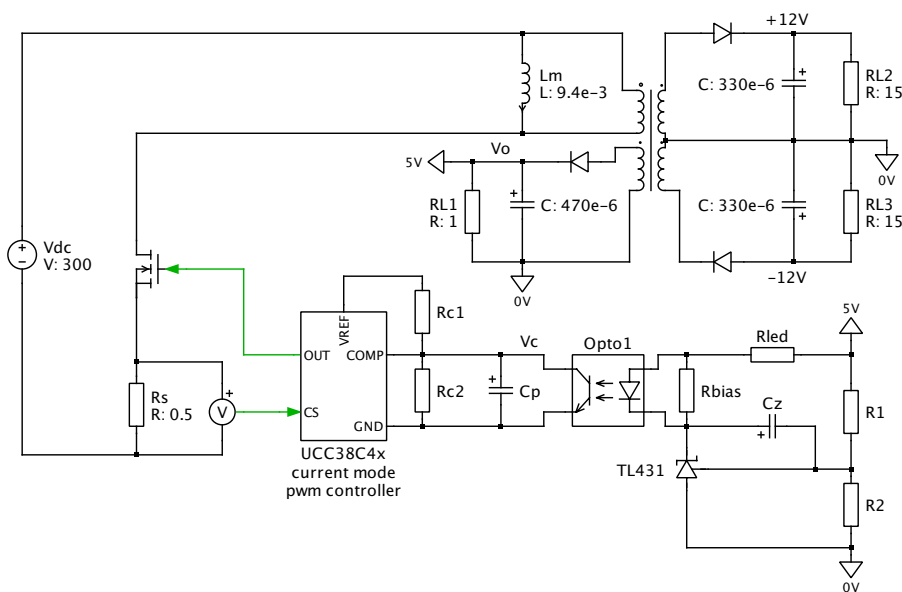


Fig. 1: Schematic of current-controlled flyback converter with a TL431 configured as a type 2 voltage controller.

The flyback converter comprises two control loops. The inner current control loop, based on peak current mode control, is realized using a UCC38C4x current-controlled PWM modulator. The outer voltage control loop is a type 2 controller, which is commonly used in power supply voltage control loops. The voltage control circuit regulates the output voltage of the 5 V winding and includes an optocoupler to maintain isolation between the input and output stages.

The voltage controller must regulate the measured 5 V output voltage over a range of loading conditions on the  $\pm 12$  V windings, which induce voltage deviations on the 5 V winding. The load resistances on the  $\pm 12$  V windings vary between 15 and 7.5  $\Omega$ . The starting point for the voltage controller design is the calculation of the converter's open-loop transfer function,  $\frac{V_o(s)}{V_c(s)}$ , which is depicted as a Bode plot. The type 2 controller is then designed in the frequency domain to ensure that it provides a sufficiently fast and stable closed-loop transient response.

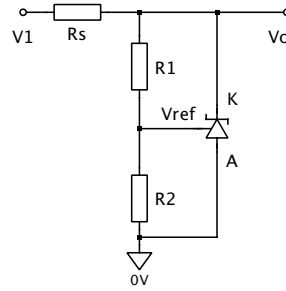


Fig. 2: Use of the TL431 to generate an arbitrary reference voltage.

In this report, an example design and verification procedure for a TL431-based type 2 voltage controller is presented. PLECS small-signal analysis tools are employed to calculate the open and closed-loop Bode plots of the system. Example models accompany this report to illustrate the use of the PLECS small-signal analysis tools and to demonstrate the operation of the complete system. These models can be found in the archive *Flyback\_tl431.zip*.

## 2 The TL431

### 2.1 The TL431 regulator

The TL431 is an adjustable shunt regulator that can be configured to provide an arbitrary reference voltage as shown in Fig. 2. The output voltage can be set to any value between  $V_{ref}$  and 36 V using two external resistors. The output voltage is given by

$$V_o = V_{ref} \left( 1 + \frac{R_1}{R_2} \right) \quad (1)$$

where  $V_{ref}$  is the onboard 2.5 V reference voltage source.

### 2.2 The TL431 type 2 error amplifier

Although the TL431 is commonly used as an adjustable voltage reference source, its onboard error amplifier can be configured as an op-amp, allowing it to be used for both voltage reference and control applications. The 1 MHz unity-gain bandwidth of its error amplifier is more than adequate for most power supply voltage control loops.

The frequency response of a type 2 controller is depicted as a Bode plot in Fig. 3. At low frequencies, the type 2 controller is similar to a PI controller, having a pole at  $0^\circ$  due to the integral action, and a zero at  $\omega_z$  due to the proportional action. However, the type 2 controller includes a high frequency pole at  $\omega_p$ , which is used to mitigate the switching ripple. The transfer function of a type 2 controller is given as follows:

$$C(s) = k_p \left( \frac{1 + s\tau}{s\tau} \right) \left( \frac{1}{1 + sT} \right) \quad (2)$$

$$= k_p \frac{1 + s\tau}{s^2\tau T + s\tau} \quad (3)$$

It can be seen from Fig. 3 that the type 2 controller is characterized by three parameters: the gain,  $A_v$ , the zero frequency,  $\omega_z$ , and the pole frequency,  $\omega_p$ . These parameters are used to calculate the terms in the transfer function as follows:

$$k_p = 10^{\frac{A_v}{20}} \quad (4)$$

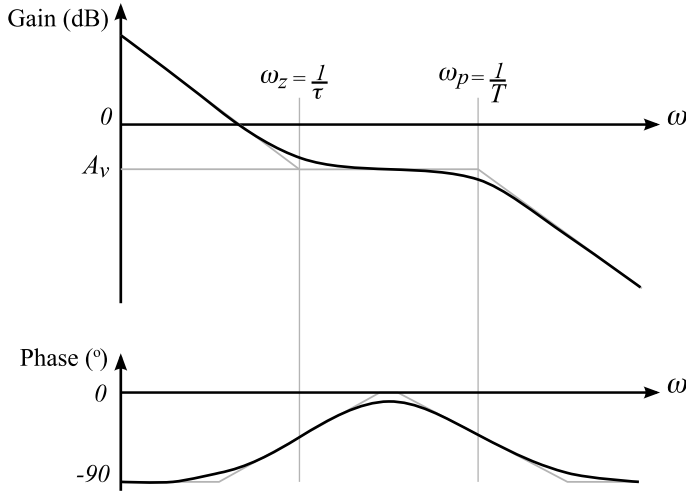


Fig. 3: Bode plot of type 2 controller.

$$\tau = \frac{1}{\omega_z} \quad (5)$$

$$T = \frac{1}{\omega_p} \quad (6)$$

The TL431 is shown configured as a type 2 controller in Fig. 4. The controller circuit, shown in Fig. 4(a), includes an optocoupler to provide isolated feedback. A single pullup resistor or a resistive divider comprising  $R_{c1}$ ,  $R_{c2}$  can be used to generate the control voltage,  $V_c$ . A resistive divider allows a maximum limit for  $V_c$  to be set, which is useful for limiting the startup current. The equivalent small-signal collector resistance,  $R_c$ , is equivalent to  $R_{c1} || R_{c2}$ .

The block diagram of the complete system is shown in Fig. 4(b). It can be seen that the TL431 control circuit includes a reference voltage source and summer in addition to the type 2 controller,  $C(s)$ .

In the TL431-based type 2 control circuit, the proportional gain is given by

$$k_p = CTR \frac{R_c}{R_{led}} \quad (7)$$

where  $CTR$  is the current transfer ratio of the optocoupler and  $R_c$  is the effective small-signal collector resistance that is formed from the parallel combination of  $R_{c1}$  and  $R_{c2}$ . The pull-down resistor  $R_{c2}$  is optional. If included, it limits the peak control voltage, in turn limiting the peak MOSFET current.

The low frequency pole is set by the components  $R_1, C_1$ :

$$\omega_z = \frac{1}{R_1 C_1} \quad (8)$$

The high frequency pole is set by the components  $R_c, C_p$ :

$$\omega_p = \frac{1}{R_c C_p} \quad (9)$$

It is assumed that  $C_p$  is much larger than  $C_{opto}$ , the output capacitance of the optocoupler.

### 3 IC modeling

Three ICs are included in the flyback converter model: the TL431 reference voltage source, the UCC38C4x current mode controller and the optocoupler. These are modeled in PLECS using simplified behavioral models.

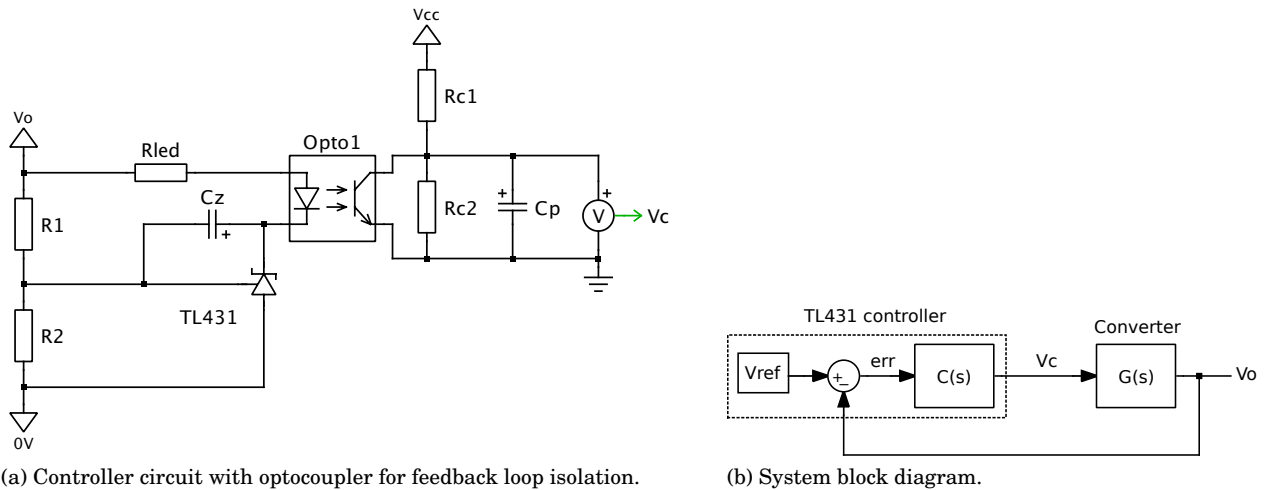
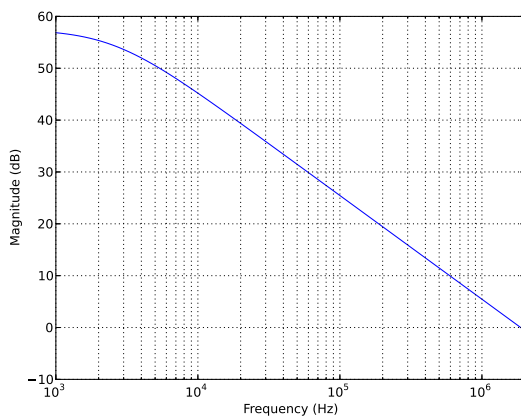
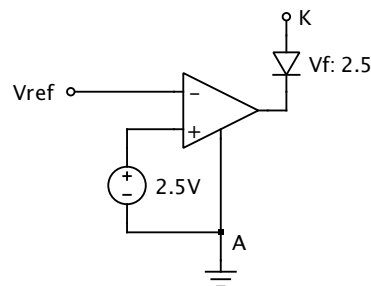


Fig. 4: The TL431 configured as an isolated type 2 controller.



(a) small-signal voltage gain.



(b) PLECS implementation.

Fig. 5: TL431 model.

### 3.1 TL431 model

A practical TL431 contains an error amplifier and a 2.5 V reference voltage source [1]. The PLECS model of the TL431 is shown in Fig. 5. The small-signal voltage gain is approximated using a first-order low-pass filter with a gain of 750 (57.5 dB) and a cutoff frequency of 2.5 kHz. The Bode plot of the small-signal voltage gain of the error amplifier is shown in Fig. 5(a). It can be seen that the unity-gain frequency is approximately 2 MHz.

It should be noted that the unity-gain frequency of the practical TL431 component is 1 MHz because the practical component does not have a true first-order characteristic. However, this difference has negligible impact on the system model, since the cutoff frequency of the control system is approximately three orders of magnitude lower than the unity gain frequency of the TL431.

The cathode current vs. voltage characteristic of the TL431 has an offset of 2.5V since the minimum cathode voltage that can be generated is equal to the reference voltage. The cathode offset voltage is modeled in PLECS using an ideal diode as shown in Fig. 5(b). Due to use of the ideal diode, the offset voltage is 2.5V, even at zero current. In a practical TL431, the cathode offset voltage is not guaranteed to be 2.5 V unless the cathode current is 1 mA. Therefore the TL431 should be correctly biased to ensure the validity of the model.

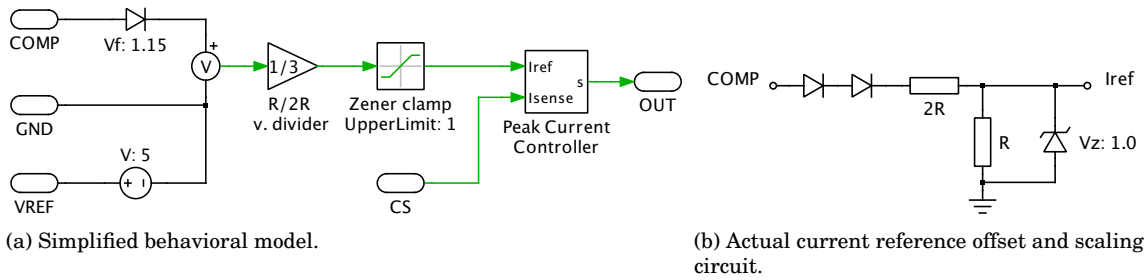


Fig. 6: PLECS model of the UCC38C4x current-mode control IC.

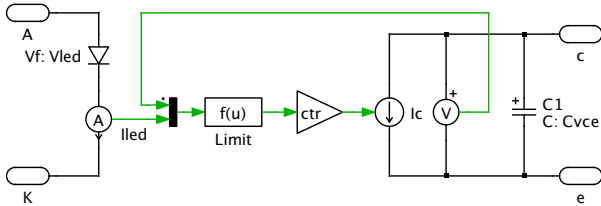


Fig. 7: PLECS optocoupler model.

### 3.2 UCC38C4x current-mode control IC model

The current controller model is based on the UCC38C4x series of current-mode PWM control ICs [2]. Internally, the UCC38C4x modulator consists of a peak current mode controller, oscillator, error amplifier, reference voltage generator, undervoltage lockout logic and current offset and scaling circuit. The simplified behavioral model of the UCC38C4x is shown in Fig. 6.

As seen in Fig. 6(a), the simplified behavioral model contains only those features that directly influence the operation of the control circuit and converter. These features are the peak current mode controller, current offset and scaling circuit and the 5 V reference voltage. The onboard error amplifier is not modeled since the control voltage is supplied by the external type 2 control circuit.

The actual current reference offset and scaling circuit found between the COMP pin and  $I_{ref}$  input of the peak current controller is shown in Fig. 6(b). The current sense circuit comprises a voltage drop of 1.15 V and a resistive voltage divider. The peak MOSFET current is therefore expressed as:

$$I_{sw} = \frac{\max(V_c - 1.15, 0)}{3R_s} \quad (10)$$

where  $R_s$  is the current sense resistor that is connected in series with the MOSFET.

### 3.3 Optocoupler model

The optocoupler is modeled using a controlled current source as shown in Fig. 7. In the linear operating region, the collector current is given by  $I_c = CTR \cdot I_{led}$ . In the saturation region, a limit is imposed on the CTR to prevent the collector voltage from becoming negative. A small capacitor that represents the collector-emitter capacitance is included in the model to prevent an algebraic loop from being formed.

It should be noted that in the PLECS optocoupler model, the CTR is assumed to be constant for simplicity. In a practical optocoupler, the CTR varies with the forward LED current, temperature, age and even between different production batches. Therefore the control circuit should be designed and tested for the lowest and highest expected values for the CTR.

Table 1: Steady-state control voltage required to generate 5 V

Load resistance ( $\pm 12$ V winding)	$V_c$
15 $\Omega$	1.96
7.5 $\Omega$	2.22

## 4 Designing the Controller

### 4.1 Converter open-loop transfer function

The first step in the design process is to obtain the open-loop transfer function of the converter. The voltage controller is then designed such that the closed-loop response of the system meets a specified bandwidth.

The transfer function of the open-loop system,  $G(s) = \frac{V_o(s)}{V_c(s)}$ , is found by adding a perturbation signal to the control signal,  $V_c$ , and measuring the response of the output voltage,  $V_o$ . In PLECS two tools can be used for calculating the open-loop transfer function: the ac sweep tool and the impulse response analysis tool. The impulse response analysis tool is much faster than the ac sweep tool for calculating the open-loop transfer function since it applies a single impulse perturbation rather than a series of sinusoidal perturbations.

Before the impulse response analysis can be run, the control voltage required to generate a 5 V output voltage at nominal load must be found because the small-signal analysis is executed by perturbing the steady-state operating point. The nominal steady-state control voltage can easily be determined by adjusting the control voltage in an open-loop simulation model until the desired output voltage is attained.

Assuming the nominal load is the minimum loading condition, with 15  $\Omega$  resistors on the  $\pm 12$  V windings and 1  $\Omega$  on the 5 V winding, the control voltage was found to be 1.96 V. The control voltages for the minimum and maximum loading conditions are given in Table 1. With the control voltage set to this value, the impulse response analysis was run, generating the Bode plot shown in Fig. 8. It can be seen that the current controlled converter exhibits first order characteristic up to 1 kHz.

**Note** To configure the impulse response analysis tool, a small-signal perturbation component must be placed in series with the constant control voltage signal. A small-signal response component must also be connected to the output voltage. In the setup parameters, the system period should be set to  $1/f_s$ , where  $f_s$  is the switching frequency. Several initialization cycles should be entered in the setup parameters to help the steady-state analysis converge before the impulse response analysis is run. Once the impulse response analysis has run, the Bode plot should be saved to a *csv* file for subsequent calculation of the closed-loop gain.

### 4.2 Controller specifications

The controller specifications for a type 2 controller can be given in terms of  $k_p$ ,  $f_z$ ,  $f_p$ . Using these specifications and the open-loop converter Bode plot, the type 2 transfer function can be calculated and the controller designed. The controller design presented in this section is not the only possible design solution. It is merely one design that provides a fast transient response and stable closed-loop system.

The proportional gain,  $k_p$ , is determined by calculating the midband voltage gain the type 2 controller must provide in order to set the cutoff frequency of the closed-loop system to a specific value. The cutoff frequency,  $f_c$ , is chosen to be 800 Hz to provide a fast response to voltage perturbations. It also allows  $k_p$  to meet the minimum gain criterion, which is explained in Section 4.5.

It can be seen from the magnitude plot in Fig. 8 that the controller must provide 3 dB of gain at  $f_c$  to bring the magnitude response to 0 dB, or unity gain. Using Eq. (4),  $k_p$  is calculated to be 1.4.

The zero frequency,  $f_z$  is chosen to be 100 Hz in order to cancel the low frequency pole of the converter. The controller pole frequency,  $f_p$ , is chosen to be 5 kHz to provide good attenuation of the switching ripple.

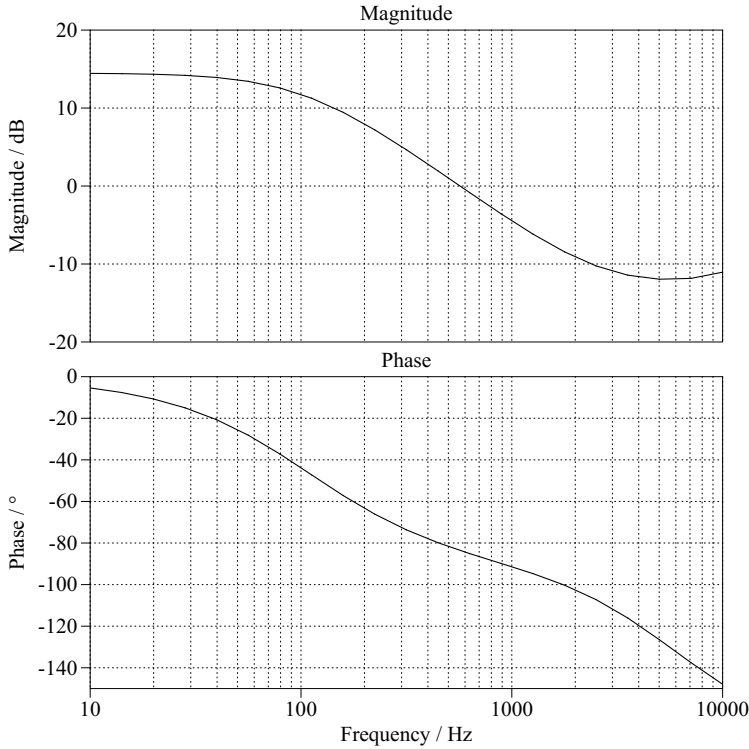


Fig. 8: Bode plot of open-loop converter transfer function,  $G(s) = \frac{V_o(s)}{V_c(s)}$ .

### 4.3 Controller design

1. The first step in designing the control circuit is to set the reference voltage to 5 V. Using Eq. (1) and selecting the bias current in the resistive divider to 0.25 mA, resistors  $R_1$  and  $R_2$  were calculated to be 10 k $\Omega$ .
2. The TL431 must have a minimum bias current of 1 mA in order to provide its stated reference voltage of 2.5 V [1]. The resistor  $R_{led}$  is calculated to provide a maximum bias current,  $I_{led\ max}$ , for the TL431 of 2 mA. The maximum bias current occurs when  $V_k$ , the cathode-anode voltage of the TL431 is at its minimum value of 2.5 V. This allows the calculation of  $R_{led}$  as follows:

$$R_{led} = \frac{V_o - V_{led} - V_{k\ min}}{I_k} = 725\Omega$$

3. Using Eq. (7), the small-signal collector resistor resistance,  $R_c$ , is calculated to achieve the required  $k_p$ :

$$R_c = \frac{k_p R_{led}}{CTR} = 812\Omega$$

$R_c$  is chosen to be 800  $\Omega$  and is implemented by setting  $R_{c1} = R_{c2} = 1600\Omega$ . Since  $V_{ref}$  in the UCC38C4x is 5 V, the peak control voltage is limited to 2.5 V and the peak MOSFET current is limited to 0.9 A in accordance with Eq. (10).

4.  $C_z$  is calculated from Eq. (8) to set the zero frequency,  $f_z$ :

$$C_z = \frac{1}{2\pi f_z R_1} = 159\text{nF}$$

5.  $C_p$  is calculated from Eq. (9) to set the pole frequency,  $f_p$ :

$$C_p = \frac{1}{2\pi f_p R_c} = 40\text{nF}$$

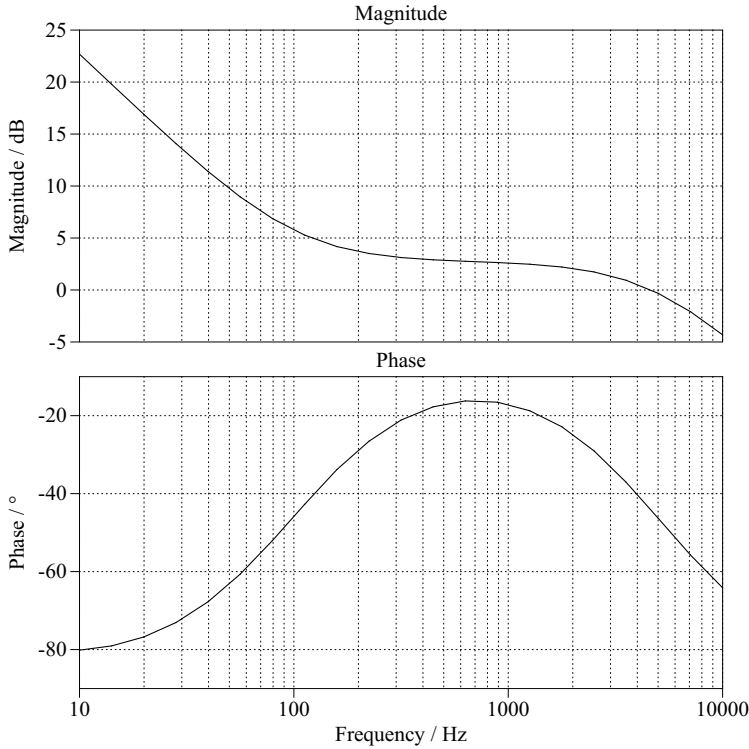


Fig. 9: Frequency response of type 2 controller.

6. To verify the controller design, an ac sweep was performed on an open-loop model of the controller. The resultant Bode plot is shown in Fig. 9. The frequency response was saved to a *csv* file for calculation of the closed-loop gain as described in Section 4.6.

#### 4.4 Verify the controller biasing

Although the design procedure given in Section 4.3 sets the type 2 controller parameters,  $k_p$ ,  $f_z$ ,  $f_p$ , correctly, the bias currents in the type 2 control circuit must be checked to ensure that the minimum required control voltage can be generated and that sufficient cathode current flows in the TL431. For the circuit shown in Fig. 4(a), the bias currents  $I_{led}$  and  $I_c$  are set by the components  $R_{led}$ ,  $R_{c1}$  and  $R_{c2}$ .

At minimum load, sufficient collector current must flow through the optocoupler to pull  $V_{ce}$  down to  $V_{cmin}$ , which was measured to be 1.96 V. Peak collector current is generated when maximum current flows through the optocoupler LED, and maximum LED current is induced when the TL431 supplies its minimum output voltage of 2.5 V. The LED current at minimum TL431 output voltage was set to be 2 mA in Step 2 of Section 4.3. Therefore if the LED current required to generate  $V_{cmin}$  is less than 2 mA, the minimum control voltage requirement is satisfied.

$$I_{led} = \frac{V_{ref} - 2V_{cmin}}{2R_c CTR} = 0.14 \text{ mA} \quad (11)$$

Therefore the minimum control voltage can be generated. If the required LED current is larger than  $I_{ledmax}$ , the cathode voltage of the TL431 would have to decrease below 2.5 V, which is not possible.

The cathode current in the TL431, equivalent to  $I_{led}$ , should also be verified. The cathode current should be at least 1 mA to ensure that the reference voltage of 2.5 V is generated. Minimum cathode current flows at maximum load, when the control voltage is at its largest value. When  $V_{cmax} = 2.22$  V is substituted into Eq. (11), it can be seen that the minimum LED current is not fulfilled. Additional bias current must therefore be added to the cathode current. This can be achieved by connecting a resistor between  $V_o$  and the cathode of the TL431 or directly across the LED in the optocoupler. A 1 k $\Omega$  resistor that is connected across the optocoupler LED provides an additional 1 mA of cathode bias current for the TL431. This



bias resistor does not change the functionality of the TL431 model, since its cathode current vs. voltage characteristic is ideal. Nevertheless, it should not be overlooked in a practical circuit.

#### 4.5 Minimum gain criterion

The minimum gain criterion exists because for small ratios of  $R_c/R_{led}$ ,  $I_{led}$  must be very large in order to pull  $V_c$  down to  $V_{c\ min}$ . The minimum gain criterion is independent of the resistor values but is dependent on  $k_p$  and thus the ratio  $R_c/R_{led}$ .

The minimum gain criterion is given as follows:

$$k_p \geq 0.5 \frac{V_{cc} - V_{c\ min}}{V_o - V_{led} - 2.5} \quad (12)$$

assuming that  $R_{c1} = R_{c2}$ . If the pulldown resistor  $R_{c2}$  is not used, the scale factor of 0.5 is omitted. If  $V_{cc} = V_o = 5\text{ V}$  and  $V_{c\ min} = 1.96\text{ V}$ , the minimum gain criterion for  $k_p$  is 1.05 or 0.44 dB. Referring to Fig. 8, it can be seen that this in turn restricts the minimum closed-loop bandwidth to approximately 600 Hz.

#### 4.6 Calculate loop gain

The TL431 controller acts as a cascade controller,  $C(s)$ , that is connected in series with the converter,  $G(s)$ , as shown in Fig. 4(b). The closed-loop transfer function of the system is given by

$$H(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} \quad (13)$$

The denominator expression,  $1 + C(s)G(s)$ , is known as the characteristic equation. If this term is equal to zero, the closed-loop response is unstable. It follows that the requirement for stability is

$$C(s)G(s) \gg -1 \quad (14)$$

This is known as the Nyquist Stability Criterion. The product of the converter and controller frequency responses,  $C(s)G(s)$ , is known as the loop gain. The distance between the loop gain and the unstable -1 point is used as a measure of stability for the closed-loop system.

The closed-loop stability is measured from the loop gain response in terms of gain and phase margin. The gain margin is the difference between the magnitude response and 0 dB at the frequency where the loop gain phase is  $-180^\circ$ . The phase margin is the difference between the phase response and  $-180^\circ$  at the frequency where the loop gain magnitude response is 0 dB. Generally, the phase margin should be greater than  $45^\circ$  and the gain margin greater than 10 dB in order to achieve a stable frequency response.

The loop gain can be calculated by adding the magnitude and phase responses of the converter and controller, which are stored in *csv* files. Example Matlab and Python functions for calculating the loop gain can be downloaded with this report.

The calculated loop gain for the voltage control loop is depicted in Fig. 10. It can be seen that the cutoff frequency is equal to its designed value of 800 Hz. The gain margin is 13 dB and the phase margin is  $70^\circ$ , indicating a stable system.

The loop gain can also be determined using the ac sweep technique. An example file is included with this report to demonstrate this technique. To speed up the loop gain sweep, the simulation should be run and the final operating point saved using Simulation Parameters > Initialization. This speeds up convergence rate of the steady-state analysis that is performed at the beginning of each ac sweep.

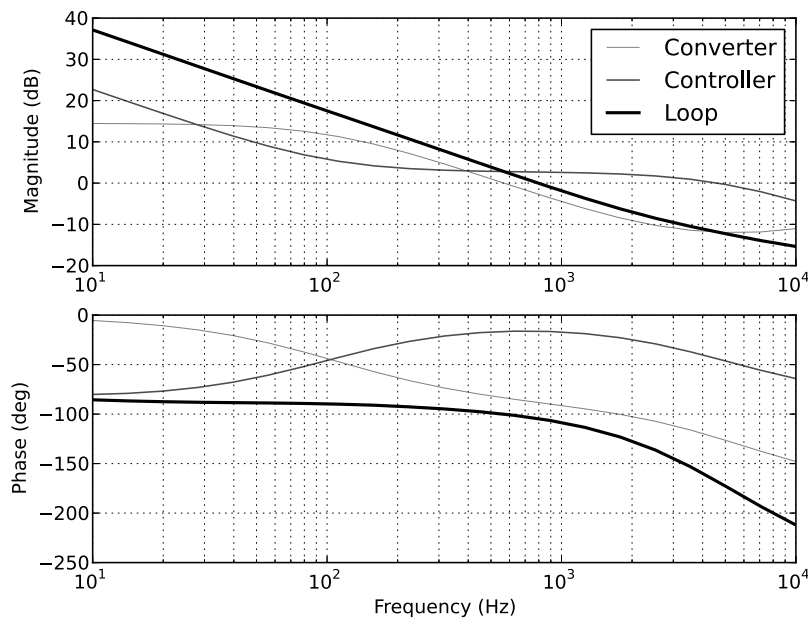


Fig. 10: Loop gain of flyback converter voltage control loop.

## 5 Conclusion

The TL431 is a commonly-used reference voltage generator that can also function as an analog controller in isolated converter control applications. Combining the control function with the voltage reference generator provides a low-cost controller implementation. The minimum gain limitation of the TL431-based type 2 controller limits the minimum cutoff frequency of the closed-loop system.

In this report, the design and implementation of a type 2 controller for a flyback converter were presented. Behavioral models of the TL431, optocoupler and current mode control IC were created in PLECS. A design procedure for the type 2 voltage control circuit, based on the small-signal tools that are integrated into PLECS, was presented. The Impulse Response Analysis tool was used to calculate the open-loop frequency response of the converter and the AC sweep tool was used to calculate the open-loop frequency response of the controller. The frequency responses were added to predict the loop gain. From the loop gain, the gain and phase margins were measured in order to predict the stability of the closed-loop system.

## References

- [1] "TL431 programmable shunt regulator," [www.fairchildsemi.com](http://www.fairchildsemi.com).
- [2] "UCC38C4x BiCMOS low power current-mode PWM controller," [www.ti.com](http://www.ti.com).

# Appendices

## A Simulation Files - PLECS Standalone

- *Flyback\_openloop\_resp.plecs*: model in which the Impulse Response Analysis tool is used to obtain the open-loop frequency response of the current-controlled converter. The result should be manually saved to csv file.
- *TL431\_controller\_sweep.plecs*: model in which the AC Sweep tool is used to obtain the frequency response of the type 2 controller. The result should be manually saved to csv file.
- *bodeadd\_csv.m*: calculates the loop gain Bode plot in Matlab by adding the frequency responses of the converter and controller, which stored in csv files
- *bodeadd\_csv.py*: implementation of the above function in the Python programming language.
- *Flyback\_closedloop.plecs*: complete model of the flyback converter and controller for verifying the transient response. The closed-loop gain can also be obtained from this model using the AC Sweep tool.

## B Simulation Files - PLECS Blockset

- *Flyback\_openloop\_resp.mdl*: model in which the Impulse Response Analysis tool is used to obtain the open-loop frequency response of the current-controlled converter. The result is written to the MATLAB workspace as a struct.
- *TL431\_controller.mdl*: model for which the transfer function of type 2 controller is calculated using the linmod function. A struct of the frequency response is returned.
- *bode\_type2\_controller.m*: helper function for calculating the Bode plot of the type 2 control circuit.
- *plbode.m*: helper function for generating Bode plots.
- *bodeadd.m*: calculates the loop gain Bode plot by adding the frequency responses of the converter and controller, which are stored as structs in the MATLAB workspace.
- *Flyback\_closedloop.mdl*: complete model of the flyback converter and controller for verifying the transient response.