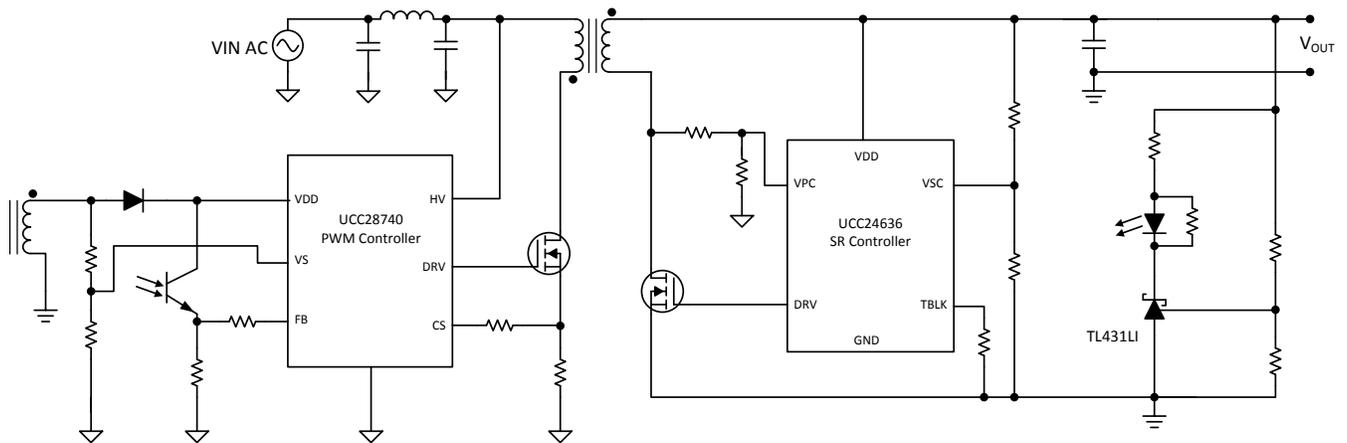


## Designing with the Improved TL431LI

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### ABSTRACT

The [TL431LI](#) is TI's latest addition to its adjustable shunt regulator family. This device is a pin-to-pin alternative to the industry standard TL431 but the TL431LI offers improvements in better temperature drift and lower reference input current that allow for a more accurate system. The higher performance of the TL431LI is critical in flyback power supplies with an optocoupler which is commonly seen in AC/DC adapters such as the common laptop battery charger adapter. [Figure 1](#) shows the TL431LI in the secondary side feedback loop as it is commonly used to drive the optocoupler for isolation. This application note will cover how designing with the TL431LI can improve the voltage output accuracy of the secondary side of a flyback power supply.



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**Figure 1. Typical AC/DC Isolated Optocoupler with A/TL431LI**

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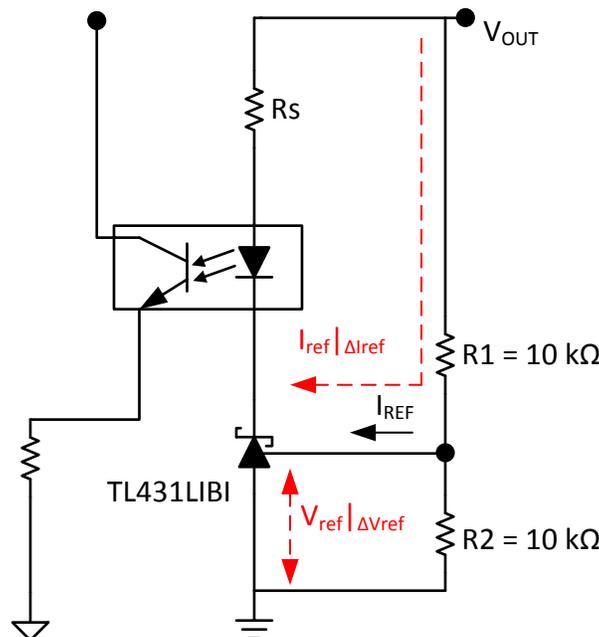
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**1 Advancements**

- Improved system accuracy due to a low maximum temperature drift
  - $V_{I(dev)} = 10 \text{ mV (C Temp)}$
  - $V_{I(dev)} = 17 \text{ mV (I Temp)}$
  - $V_{I(dev)} = 27 \text{ mV (Q Temp)}$
- Improved system accuracy due to low reference current
  - $I_{ref} = 0.4 \text{ }\mu\text{A (max)}$
  - $I_{I(dev)} = 0.3 \text{ }\mu\text{A (max)}$
- Improved stability region for load capacitors

**2 TL431LI Improved System Accuracy**

The TL431LI allows for improved system accuracy over the industry standard TL431 due to its decrease in  $V_{I(dev)}$ ,  $I_{ref}$ , and  $I_{I(dev)}$ . The primary advantage is from the lower temperature drift,  $V_{I(dev)}$ , that allows for less output voltage deviation due to temperature excursions while in operation. The  $V_{I(dev)}$  can be as low as 17 mV in the common industrial temperature range of -40°C to 85°C which is advantageous in critical in AC/DC adapters as they operate at high temperatures. Figure 1 shows a typical example of an AC/DC isolated optocoupler application. In flyback converters, the accuracy of the output is dependent on the error of the feedback loop which includes the errors from the TL431LI, optocoupler, and external resistors. Managing this error can often be a challenge to designers when the shunt regulator can contribute a high error of 1% or greater over temperature. The TL431LI with feedback and loop error can be seen in Figure 2.



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**Figure 2. Flyback secondary side with TL431LI**

## 2.1 Shunt Voltage Reference Error

The error of  $V_{OUT}$  is dependent on environmental and system factors and it is important to take these considerations into account to maximize the accuracy of the system. The simplified output voltage of a flyback converter is Equation 1. This equation is typically used to estimate the output of the device but it does not take into account temperature deviation or other voltage scaling factors. This is because real world shunt regulators have limited gain and suffer from cathode voltage modulation.

$$\text{Simplified } V_{OUT} = V_{ref} \times \left(1 + \frac{R1}{R2}\right) + R1 \times I_{ref} \tag{1}$$

Equation 2 shows a more accurate error of  $V_{OUT}$  as both  $V_{ref}$  and  $I_{ref}$  modulations are taken into consideration which will be explained in later equations.

$$\text{Expanded } V_{OUT} = V_{ref} (\Delta V_{ref} |_{total}) \times \left(1 + \frac{R1}{R2}\right) + R1 \times (I_{ref} (\Delta I_{ref} |_{total})) \tag{2}$$

The  $V_{ref} (\Delta V_{ref} |_{total})$  in Equation 2 refers to the internal reference voltage of the shunt regulator. Equation 3 shows the addition of all voltage deviations for  $V_{ref}$  to yield  $V_{ref} (\Delta V_{ref} |_{total})$ .

$$V_{ref} (\Delta V_{ref} |_{total}) = V_{nom} \times (1 \pm \text{Initial Accuracy}) \pm V_{I(dev)} + ((I_{KA} - I_{test}) \times Z_{KA}) + \Delta V_{ref} |_{\Delta V_{KA}} \tag{3}$$

$\Delta V_{ref} |_{Initial Accuracy}$  refers to the error from the initial accuracy deviation of the  $V_{ref}$ . Initial accuracy is typically defined on TL431LI as 1% (A grade) or 0.5% (B grade) at 25°C. The only way to minimize initial accuracy error is to design with the highest grade of TL431LI. The initial accuracy is shown in Equation 4 as this deviation affects the nominal voltage reference..

$$\Delta V_{ref} |_{Initial Accuracy} = 1 \pm \text{Initial Accuracy} \tag{4}$$

$\Delta V_{ref} |_{Temperature Drift}$  is the  $\Delta V_{ref}$  due to temperature deviations from 25°C and is shown in Equation 5. This voltage deviation can be minimized by choosing the highest grade of TL431LI. Both  $\Delta V_{ref} |_{Initial Accuracy}$  and  $\Delta V_{ref} |_{Temperature Drift}$  affect the  $V_{ref}$  of all TL431LI regardless of the  $V_{KA}$  voltage.

$$\Delta V_{ref} |_{Temperature Drift} = \pm V_{I(dev)} \tag{5}$$

Unlike the other  $\Delta V_{ref}$  errors described previously, the  $\Delta V_{ref} |_{Dynamic Impedance}$  and  $\Delta V_{ref} |_{\Delta V_{KA}}$  are conditional.  $\Delta V_{ref} |_{Dynamic Impedance}$  is an error that is dependent on the  $I_{KA}$  of the TL431LI. This error stems from the deviation of  $I_{KA}$ . Having  $I_{KA}$  fluctuate from  $I_{test}$  to  $I_{KA}$  as shown in Figure 3, can produce a deviation in  $V_{ref}$  which is also shown in Figure 3. The closer the TL431LI  $I_{KA}$  is biased to  $I_{test}$ , the less the  $\Delta V_{ref} |_{Dynamic Impedance}$  deviation affects the output. The  $\Delta V_{ref} |_{Dynamic Impedance}$  deviation can be calculated. in Equation 6.

$$\Delta V_{ref} |_{Dynamic Impedance} = (I_{KA} - I_{test}) \times Z_{KA} \tag{6}$$

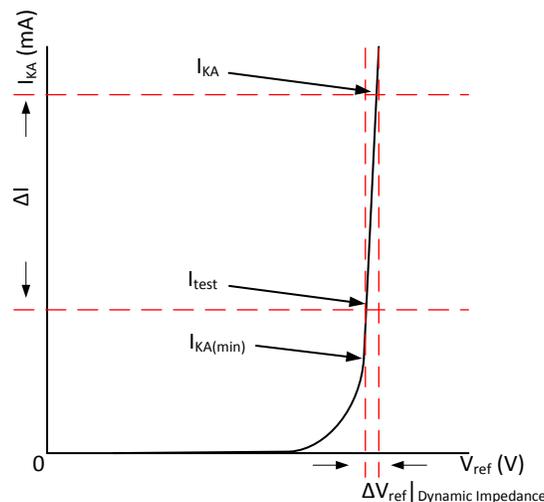


Figure 3. Dynamic Impedance

The  $\Delta V_{ref} |_{\Delta V_{KA}}$  is conditional based on the  $V_{KA}$  of the system. The greater the  $V_{KA}$  is over  $V_{ref}$  the larger the deviation will be. While these two voltage deviation do not affect the TL431LI in all conditions, it is important to know when they do apply because they are frequently ignored and their effect can be significant.

$$\Delta V_{ref} |_{\Delta V_{KA}} = (V_{KA} - V_{nom}) \times \frac{\Delta V_{ref}}{\Delta V_{KA}} |_{V_{KA} \leq 10V}, \text{ Valid when } V_{KA} \leq 10V \quad (7)$$

$$\Delta V_{ref} |_{\Delta V_{KA}} = ((V_{KA} - 10V) \times \frac{\Delta V_{ref}}{\Delta V_{KA}} |_{V_{KA} > 10V}) + ((10V - V_{ref}) \times \frac{\Delta V_{ref}}{\Delta V_{KA}} |_{V_{KA} \leq 10V}), \text{ Valid when } V_{KA} > 10V \quad (8)$$

The  $I_{ref}$  of the TL431LI also has a temperature drift,  $I_{I(dev)}$ , that is often ignored. The value of  $I_{I(dev)}$  can be larger than the nominal  $I_{ref}$  which can be seen in Equation 10. The reason the  $I_{ref}(\Delta I_{ref} |_{total})$  is important is because the input  $I_{ref}$  causes an inequality in the feedback resistors which changes the effective DC feedback ratio. The  $I_{ref}$  deviation is shown in Equation 9. This error is largely based on the value of R1 as R1 will turn the  $I_{ref}$  deviation to a  $V_{OUT}$  deviation. One design challenge is to balance the size of the R1 resistor to between limiting the leakage current and lowering the error. This balance is easier when the  $I_{ref}$  is a low value such as the 0.4  $\mu A$  on the TL431LI.

$$I_{ref}(\Delta I_{ref} |_{total}) = I_{ref} \pm I_{I(dev)} \quad (9)$$

$$\Delta I_{ref} |_{Temperature\ Drift} = \pm I_{I(dev)} \quad (10)$$

TL431LI and TL431 error is calculated by the difference between the maximum values and the nominal values using Equation 2. Further details of this error calculation will be demonstrated in Section 3. The typical  $V_{KA}$  will include the effects of initial accuracy, dynamic impedance, and  $\Delta V_{KA}$ . The typical  $V_{KA}$  does not include the effects of temperature because the temperature drift can drift high or low and thus the typical can be 0.

### 3 TL431LI vs Industry Standard TL431 Error in Flyback Converters

The TL431LI has several improvements over the industrial standard TL431 in  $V_{I(dev)}$ ,  $I_{ref}$ , and  $I_{I(dev)}$ . How these individual differences compare in regards to error will be discussed in this section. The biggest improvement in the TL431LI is the temperature drift on all available temperature options. In the C grade (0°C to 70°C) and I grade (-40°C to 85°C), the TL431LI has half the temperature drift of the TL431. Table 1 shows an example of how much percent error the 5V output will have. The TL431LI I grade is close to 0.7% more accurate over its TL431 counterpart. This error on  $V_{ref}$  will stay constant as the output voltage increases so even with a  $V_{KA}$  of 5V, the percent error is the same as a  $V_{KA}$  of 2.945V.

**Table 1. TL431LI Temperature Drift,  $V_{I(dev)}$ , Error Calculation Comparison Estimate**

	$V_{I(dev)}$ (Max) for I grade (-40°C to 85°C)	Percent Error of a 2.495 V Output	Percent Error of a 5 V Output
Industry Standard TL431	34 mV	1.36 %	1.36 %
TL431LI	17 mV	0.68 %	0.68 %

Table 2 shows a comparison of the accuracy of an industry standard TL431 and the TL431LI in terms of  $I_{ref}$ . When performing error budgeting, due to the part to part variation, the deviation from the maximum  $I_{ref}$  vs typical  $I_{ref}$  will be the error because the TL431LI device will always consume  $I_{ref}$ . In the case of a 5V  $V_{OUT}$ , the error of the system can be reduced by using a TL431LI.

**Table 2. TL431LI  $I_{REF}$  Error Calculation Comparison Estimate**

	$I_{REF}$ (Max)	$I_{REF}$ (Typ)	$\Delta I_{ref}$	R1	mV Error of a 5 V Output	Percent Error of a 5 V Output
Industry Standard TL431	4.0 $\mu A$	2.5 $\mu A$	1.5 $\mu A$	10 k $\Omega$	15 mV	0.30 %
TL431LI	0.4 $\mu A$	0.2 $\mu A$	0.2 $\mu A$	10 k $\Omega$	2 mV	0.04 %

The lowered  $I_{ref}$  accuracy advantage is also reflected in the  $I_{ref}$  tolerance over temperature,  $I_{I(dev)}$ . The TL431LI has a lower maximum deviation which can result in a lower error. A comparison showing the benefit of TL431LI's  $I_{I(dev)}$  is shown in [Table 3](#). The accuracy advantage of the TL431LI comes from a direct reduction of  $\Delta I_{ref}$  from 1.5  $\mu\text{A}$  (max from 431 competition) to 0.2  $\mu\text{A}$  (max) which is a 7.5x reduction. By looking at the  $I_{ref}$  and  $I_{I(dev)}$  errors combined it is possible to have a more precise and accurate output by using the TL431LI.

**Table 3. TL431LI  $I_{I(dev)}$  Error Calculation Comparison Estimate**

	$I_{I(dev)}$	R1	mV Error of a 5 V Output	Percent Error of a 5 V Output
Industry Standard TL431	2.5 $\mu\text{A}$	10 k $\Omega$	25 mV	0.50 %
TL431LI	0.4 $\mu\text{A}$	10 k $\Omega$	4 mV	0.08 %

When looking at error, it is important to calculate the full error using [Equation 2](#). The previous tables showed an estimate assuming all errors are isolated, but that is not the case in the real world. For example, the  $I_{I(dev)}$  error is dependent on R1 so the error on R1 will increase the overall total deviation of  $I_{I(dev)}$ . When looking at the overall system deviation for maximum worst case error, it is important to look at both the minimum and maximum worst case and compare them to the typical. [Table 4](#) takes [Equation 2](#) equation into consideration and assumes the schematic will be [Figure 2](#). Assume that R1 and R2 have 0.5% error and the  $I_{KA}$  is 1 mA. Looking at the worst case error, the TL431LI has over 1% accuracy savings.

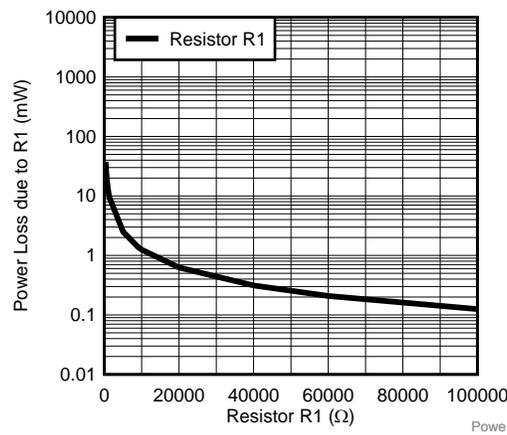
**Table 4. TL431LI Total Error Comparison Estimate**

	Worst Case Lower $V_{OUT}$ (V)	Typical $V_{OUT}$ (V)	Worst Case Upper $V_{OUT}$ (V)	Worst Case Error
TL431BI	4.848 V	5.015 V	5.148 V	3.340 %
TL431LIBI	4.891 V	4.992 V	5.069 V	2.021 %

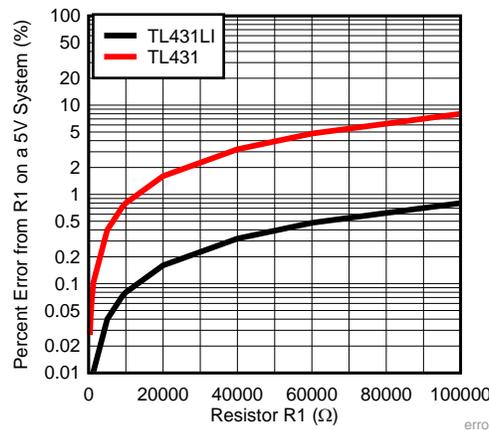
One of the drawbacks of a shunt regulator is the overall high error due to the high initial accuracy and temperature coefficient. With the TL431LI it is possible to lower the BOM cost and/or increase the system accuracy and efficiency compared to an industry standard TL431. Typically the main selection of a shunt regulator depends on the accuracy and temperature grade. The most common industry initial accuracy grades are 1% and 0.5%. If the total error of a shunt regulator can be improved by at least 1 % by using the TL431LI due to its improved specification, then it is possible to realize multiple system cost benefits. For example, a 0.5% TL431BI with 0.5% resistors can be replaced by a 1% TL431LIAI with 1% resistors and achieve a similar or improved system accuracy and BOM savings.

## 4 TL431LI Power Savings

In a typical optocoupler application such as [Figure 2](#), there is a continuous power loss due to  $I_{KA}$  and  $I_{res}$ . In this example,  $I_{res}$  refers to the current through the gain resistors R1 & R2. In this application, the  $I_{KA}$  is commonly set as low as possible to save power but it is limited by the  $I_{KA(min)}$  of TL431LI. This causes there to be a continuous power loss of at least 1 mA due to the TL431LI biasing. The  $I_{res}$  causes additional power loss that adds on to the  $I_{KA}$ . Unlike the  $I_{KA}$ , the  $I_{res}$  can be lowered by increasing the value of R1 but increase an increase in R1 will error of the system. In [Figure 4](#) and [Figure 5](#) it is possible to see how using the TL431LI allows you to use larger gain resistors while maintaining a low system error due to a lower  $I_{ref}$  compared to a TL431. To save even more power, it is recommended to use a ATL431LI or ATL431 as the  $I_{KA(min)}$  is lower than 80  $\mu\text{A}$ .



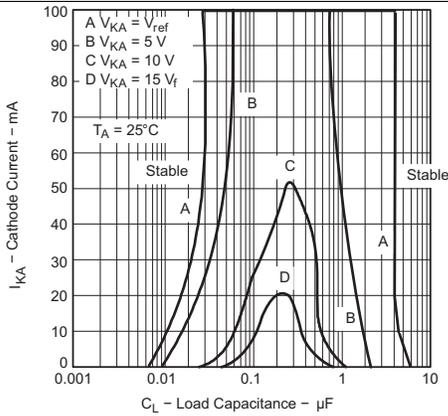
**Figure 4. Continuous Power Loss from R1 and R2 in a 5V system**



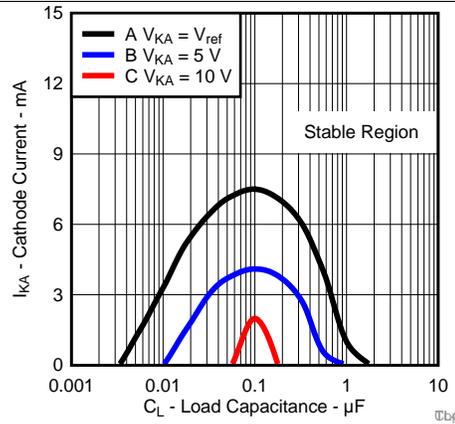
**Figure 5. TL431LI R1 vs Accuracy**

## 5 TL431LI Stability

In the Industry standard TL431, stability is one of the most common design challenges. Due to the low system BOM cost nature of these devices, there are boundaries of instability that are dependent on the  $C_{Load}$  on the  $V_{KA}$  pin. One problem with stability is that the industry is not consistent on the areas of stability due to each company having their own variation. Typical TL431 stability charts have a large boundary of instability at low currents and low  $V_{ka}$  as shown in [Figure 6](#). The result of this is that very large  $C_{LOAD}$  values must be used to ensure stability and decoupling or a very small capacitor with reduced decoupling effects. Also the area of instability varies from lot to lot and temperature so it is always important to add a margin of error from the instability line to ensure that there is significant margin.



**Figure 6. Stability Boundary Conditions of TL431**



**Figure 7. Stability Boundary Conditions for TL431LI**

In the TL431LI, an improvement in stability is depicted in [Figure 7](#). This improvement allows for designers to be able to use a 2.2µF C<sub>Load</sub> at voltage outputs while still maintaining stability. Due to this, the TL431LI is more design friendly than industry standard TL431s that cannot tolerate a 2.2µF C<sub>Load</sub>.

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## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

<b>Changes from Original (August 2018) to A Revision</b>	<b>Page</b>
• Changed document throughout .....	<a href="#">2</a>

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