Application Note

Designing Stable Isolated Power Supplies with Shunt References

ABSTRACT

Shunt regulators of the 431 family (TL431, TL431LI, ATL431 and ATL431LI) behave as a voltage comparator when operated in open loop. Voltage is sensed at the reference pin and output is taken from the cathode pin as shown in Figure 2-1. A shunt voltage reference is commonly used in the feedback loop of the PWM controllers in switching power supplies. Shunt regulators are very popular for its low cost and built-in precise reference. It acts as an error amplifier in the feedback loop with the optocoupler. It senses the output voltage and trigger the optocoupler for the PWM controller feedback. This application note explains the comparator mode operation and discusses the key design considerations for the 431 family in the comparator mode.

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1 Trademarks

All trademarks are the property of their respective owners.

2 Comparator Mode

The 431 family of TI shunt regulators are used in the comparator mode by opening the DC feedback path, when there is no DC current from cathode to reference pin. Below are examples of circuits for shunt regulators in the comparator mode. Figure 2-1 shows the simple comparator circuit and Figure 2-2 shows the typical type II compensation which is used in isolated power supply designs with optocoupler feedback. This section discusses the specs of the family 431 in comparator mode.

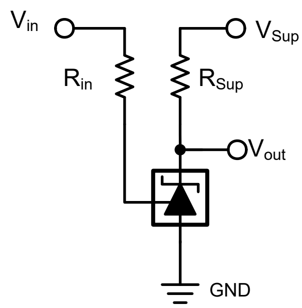


Figure 2-1. Basic Comparator Mode

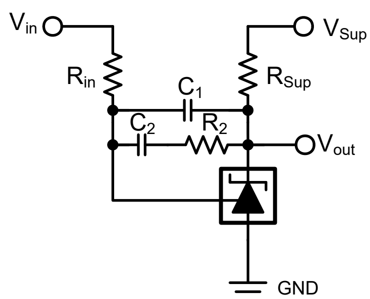


Figure 2-2. Comparator with Type 2 Compensation

2.1 Input Threshold Voltage (VIT)

The threshold voltage (VIT) for 431 shunt regulators in comparator mode is equal to the reference voltage of the device. Comparator changes the output state when input crosses VIT level. Table 2-1 lists VIT levels for 431 shunt regulators

Table 2-1. Typical VIT of Shunt Regulators

Devices	Typical Threshold (VIT) in Comparator Mode (V)
TL431, TL431LI	2.495
ATL431, ATL431LI	2.5
TLV431, TLVH431	1.24

2.2 Output Levels (VOH , VOL)

The comparator operation for shunt devices operates in 2 modes.

- **VIN = 0:** The device stays in the off condition in this state. The cathode current IKA = 0 and output voltage VKA (VOH) = Vsup when the input voltage is Vin = 0 for the device.
- **0 < VIN < VIT:** The reference pin starts taking a few nA current as soon as the input voltage (Vin) goes above 0 V and this will establish IKA in the range of few uA which will be much lower compared to IKAmin of the device . Figure 2-1 circuit is tested with Rin = 100 kΩ, Rsup = 10 kΩ and IKA vs Vin. Figure 2-3 shows the typical variation of IKA when VIN < VIT. This plays an important role in deciding the upper limit of Rsup for VOH.
- **VIN ≥ VIT:** The reference pin is saturated around VIT and Iref increases with Vin. The cathode pin turns on and VKA gets saturated around a fixed voltage (VOL).

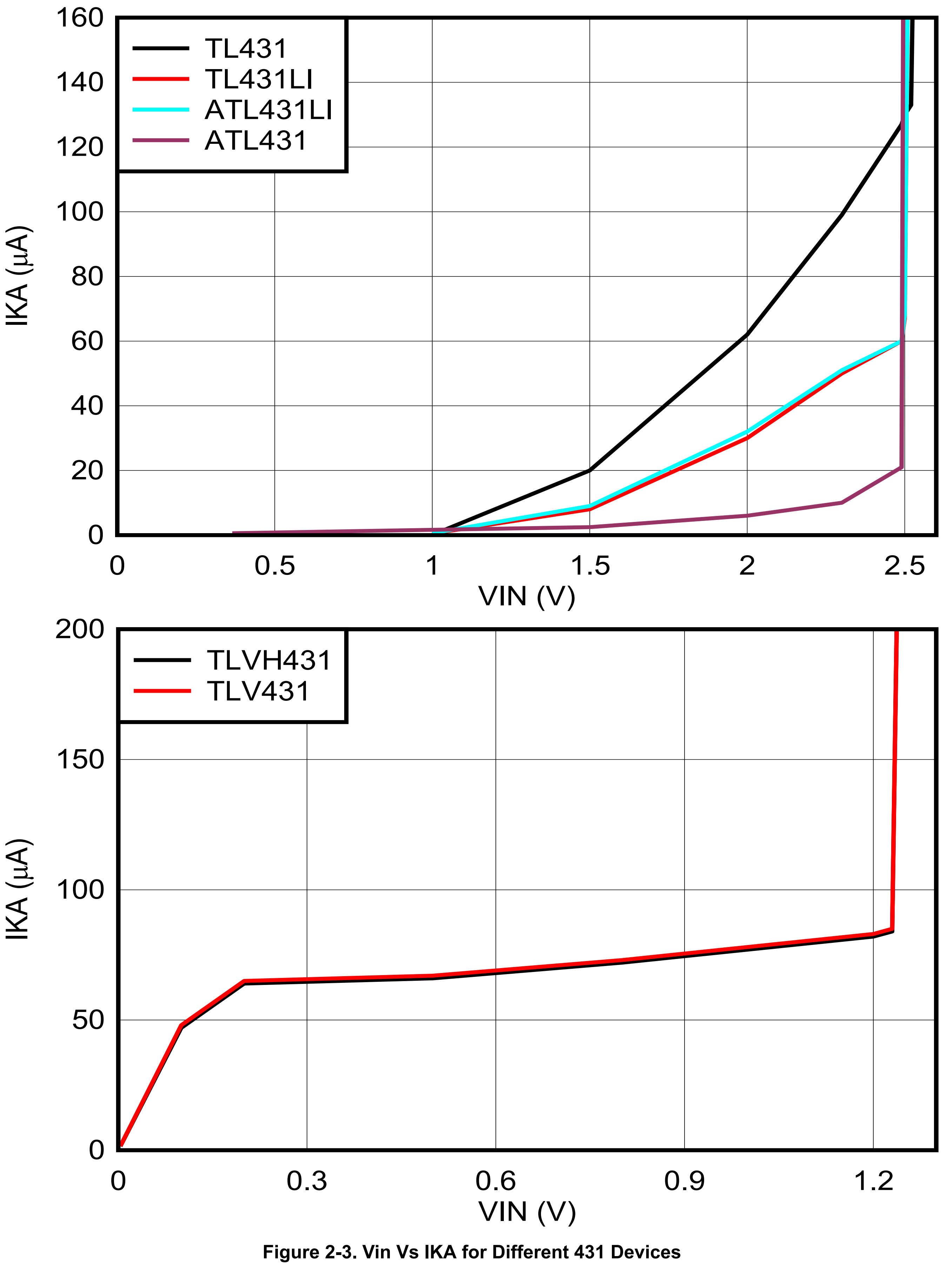


Figure 2-3. Vin Vs IKA for Different 431 Devices

Table 2-2 lists typical VOL across different shunt regulators –

$$\mathrm{VKA} = \begin{cases} \mathrm{V_{Sup}}, & \mathrm{V_{IN}} < \mathrm{V_{REF}} \\ \mathrm{V_{OL}}, & \mathrm{V_{IN}} > \mathrm{V_{REF}} \end{cases} \tag{1}$$

Table 2-2. Typical Low Level (VOL) Voltage When Shunt Regulator is ON

Devices	Typical VOL (V)
TL431, TL431LI, ATL431, ATL431LI,	2
ATL431	1

Please refer to app note slva987 for more details about the VOL level.

2.3 Propagation Delay

The Total Propagation delay of the 431 devices depend on the internal response time and rise/fall time of VKA. Rise time depends on the Rsup and the total capacitor from cathode to ground. Fall time depends on the total capacitor from cathode to ground and internal resistance in the comparator mode. Section 4.2 discusses the delay time for 431 devices in detail.

3 Design Parameters for Comparator Mode

This section discusses the design parameters consideration for components (resistor and capacitor) selection as shown in Figure 2-1

3.1 IREF (Reference Current)

IREF does not vary as long as VIN stays below the threshold voltage. Once VIN crosses the comparator threshold, voltage at reference pin (VREF) remains constant around the threshold voltage and IREF starts increasing with VIN.

$$I_{REF} = \frac{V_{In} - V_{REF}}{R_{In}} \tag{2}$$

Choose the Resistor RIn so that IREF does not go more than a few µA for maximum possible VIN. This affects VOL, VIT and the switching time at the cathode terminal.

3.2 IKA (Cathode Current)

IKA remains close to 0 as long as VIN stays below the threshold voltage and the cathode voltage is equal to the supply voltage. The supply voltage must be less than the maximum recommended VKA of the shunt regulator. Once VIN crosses the threshold voltage, the cathode terminal starts conducting and cathode voltage remains close to VOL level.

$$\mathrm{IKA} \quad = \frac{(\mathrm{Vsupply} - \mathrm{VOL})}{\mathrm{Rsup}} \tag{3}$$

IKA must be in the limits of the maximum recommended operating condition of the device. Please refer to app note slva987 for the impact of IREF and IKA on VOL of the device.

Rsup must be chosen such that IKA in the ON condition is much higher compared to IKA in the OFF condition to make sure that VOH does not degrade.

$$\mathrm{Rsup}\left(\mathrm{Max}\right) = \frac{\mathrm{VOH(Min)}}{\mathrm{IKA\ @(VIN < VIT)}} \tag{4}$$

3.3 Stability

External capacitors that are connected to the shunt regulator and IKA affect the stability of the 431 comparators. The 431 devices are stable for a full range of IKA if there is no capacitor connected on any of the pins. The designer may want to connect a capacitor to suppress noise and support high inrush. A load capacitor is connected between cathode to GND to support the load inrush current. Designers may add a capacitor at the reference pin to suppress noise on the input pin. 431 comparators may need Type 1 or Type 2 compensation in power supply designs to make whole loop stable with the pole inserted by the optocoupler. These capacitors introduce extra poles in the system and may lead to unstable VOL if the pole is located at an undesired location. This section explains how to select the capacitors so that VOL is stable.

3.3.1 Load Capacitor (Cathode to Anode)

The 431 family does not need any load capacitor for stability in the comparator mode. However, load capacitors can be connected at the cathode pin in case there is high inrush current demand in the system. Load capacitors increase the propagation delay and affect the stability of the system. Stability analysis was done on the circuit shown in Figure 3-1.

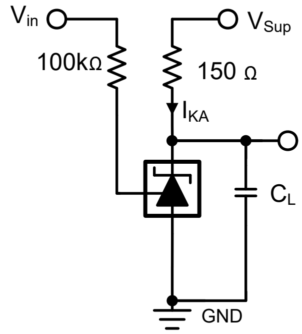


Figure 3-1. Test Circuit for Stability of TL431 in Comparator Mode

Vin is ramped up from 0 V to 3 V to turn on the comparator. Stability of the comparator mode is checked for by sweeping IKA from IKA minimum to IKA maximum for TL431, TL431LI. Figure 3-2 shows the unstable VOL behavior when 0.1 uF capacitor was connected between the cathode to anode terminal or TL431 for IKA of 1mA. Figure 3-3 shows stable VOL for same IKA condition when there is no capacitor .

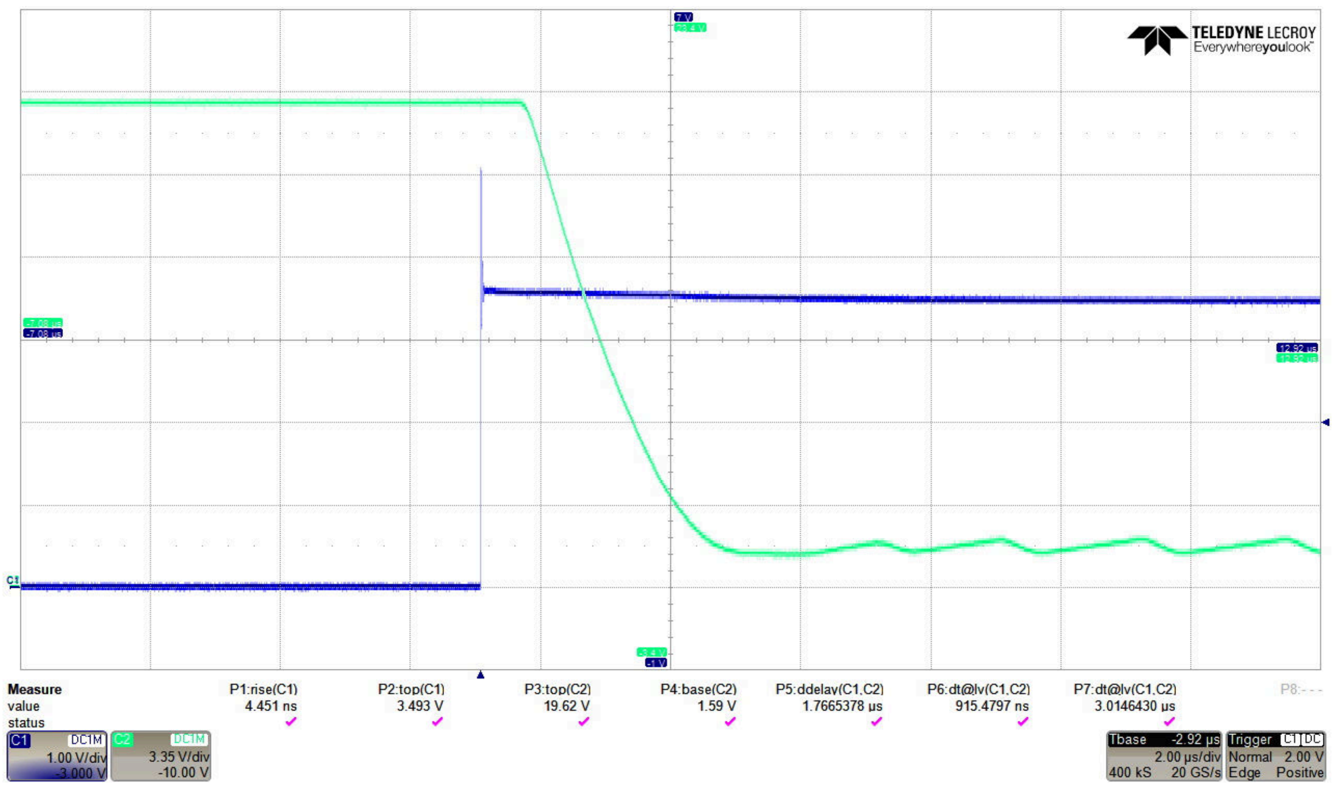


Figure 3-2. Unstable Output

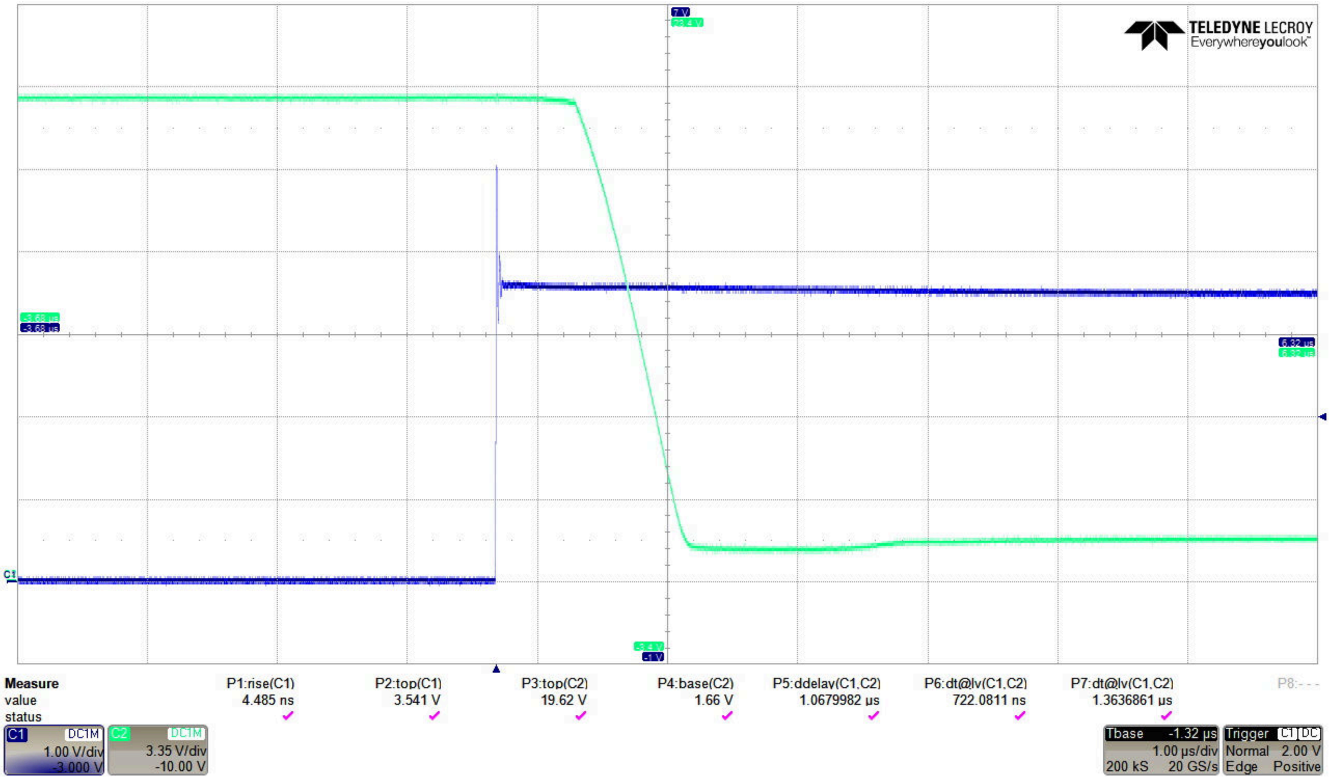
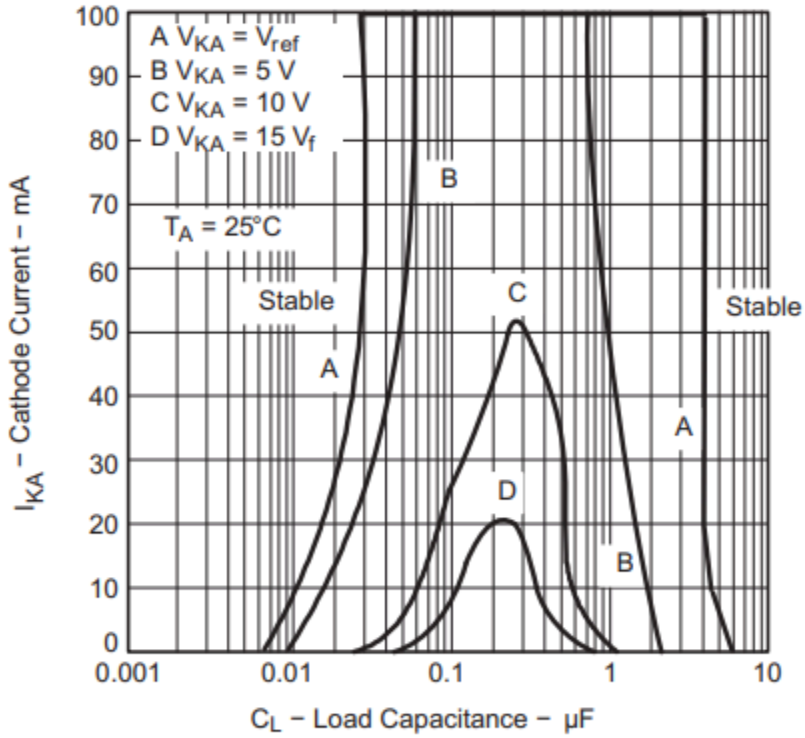


Figure 3-3. Stable Output

The Comparator mode operation follows the stability plot of VREF =VKA as specified in the data sheet. Figure 6 shows the stability plot of TL431 specified in the data sheet. It follows the stable region for plot A in Figure 3-4. The capacitors and current combination out side of the curve A (VKA = VREF) is stable in comparator mode. Further recommendations are given in the app note slva482 for choosing a stable capacitor across the temperature.



The areas under the curves represent conditions that may cause the device to oscillate. For curves B, C, and D, R2 and V+ are adjusted to establish the initial V_{KA} and I_{KA} conditions, with C_L = 0. V_{BATT} and C_L then are adjusted to determine the ranges of stability.

Figure 7-18. Stability Boundary Conditions for All TL431B, TL432, SOT-23, SC-70, and Q-Temp Devices

Figure 3-4. TL431 Stability Plot

Note: A design that has a capacitor at the reference pin of the 431 device to suppress the input noise. This adds one extra pole in the system and alters the stability curve recommended in the data sheet. TI does not recommend this and the designer must be very careful and qualify this on silicon.

3.3.2 Compensation in Comparator Mode in Feedback of PWM Controller

The 431 family devices are commonly used for sensing the output of the SMPS and providing feedback to the PWM controller IC through the optocoupler to improve the efficiency of the power supply design as shown in the Figure 3-5.

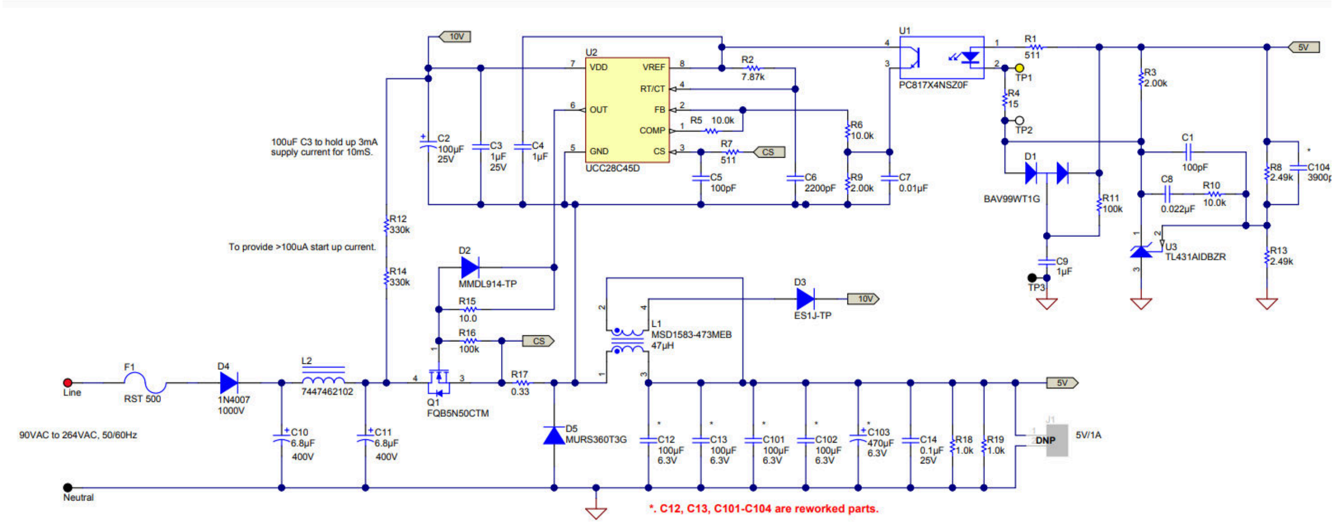


Figure 3-5. Power Supply Design Example

The external components and devices such as the optocoupler and feedback compensation network of the PWM controller affects the stability of the system. TL431 is regarded as a trans-conductance amplifier, so high trans-conductance gain is required in compensation application. A feature of TL431 is that when IKA is low, it’s trans-conductance gain is also low, however, when IKA rises, trans-conductance gain grows quickly, hence this sets minimum limitation of IKA. A compensation circuit of second order is widely used to compensate the original poles and of the feedback system and improve the phase margin thus stability of the system. Application note SLUA671 explains the calculation of the compensation components {R8, C1, C8, R10}.

4 Design Example

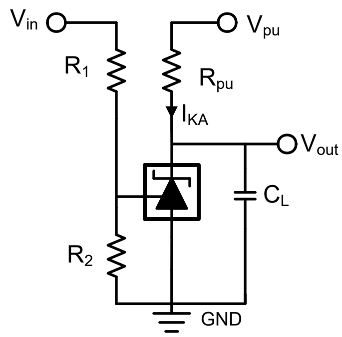


Figure 4-1. Comparator Mode Design Example

4.1 Input Parameters

Table 4-1 lists all the input conditions for a design example show in Figure 4-1

Table 4-1. Design Parameters

Parameter	Value
VPU	10 V
Vin	Threshold = 5, Maximum Vin = 6 V
Device	TL431 [VREF = 2.495, IKA maximum = 100 mA , IKA min = 1 mA]
IKA (as per design budget)	10 mA

Calculations

- Max Iref Variation = 100 uA
- R1 can be calculated from equation 3 , R1 = 35 kΩ
- R2 can be calculated from equation 4.

$$R_2 = \frac{R_1 x V_{REF}}{V_{KA} - V_{REF}} \tag{5}$$

- R2 - 35 kΩ
- RPU can be calculated from equation 3 , RPU = 800 Ω
- This design does not use any load capacitor. However, the designer can put a load capacitor from cathode to anode as discussed in Section 3.3.

4.2 Specs of Comparator Mode

- **VOL:** As table 2 suggests, TL and ATL devices have VOL close to 2 V and TLV and TLVH devices have VOL close to 1 V. Please refer to application note SLVA987 for more detail of VOL variation over IKA, IREF and temperature.
- **Propagation delay:** Designers prefer fast response in the comparator mode in their designs. Faster response of the comparator mode in power vsupply design saves power by switching the PWM controller faster in the design example given in the figure. Table 4-2 lists the typical TPHL for 431 devices when the supply is ramped up from 4.5 V to 6 V to the output of the comparator settles within 5% of the VOL value for the no load capacitor.

Table 4-2. Typical Propagation Delay (Settled Response) of Devices

Device	TPHL (µs)
TL431	1.5
TL431LI	1.2
ATL431	10
ATL431LI	1.2

Below are the scope shots for TPLH for different devices.

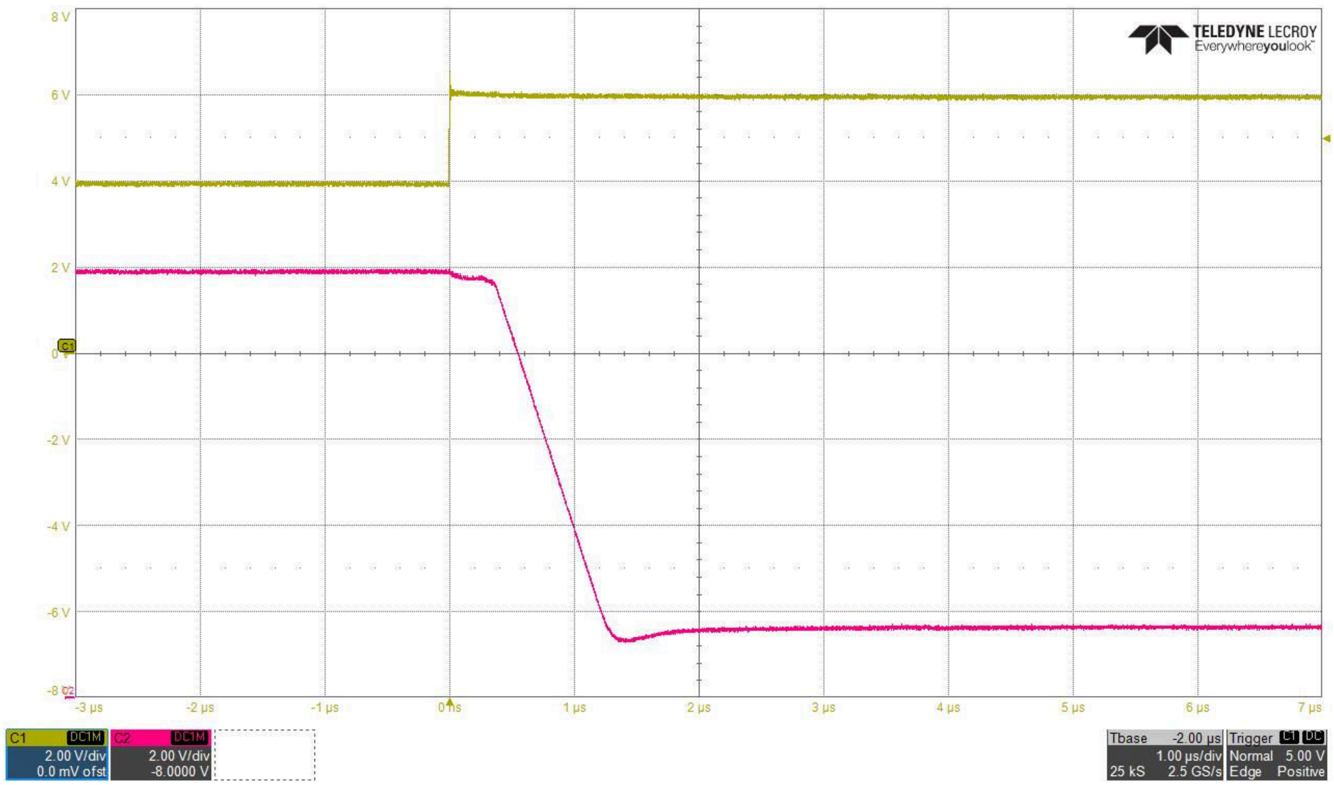


Figure 4-2. Propagation Delay (TPLH): TL431

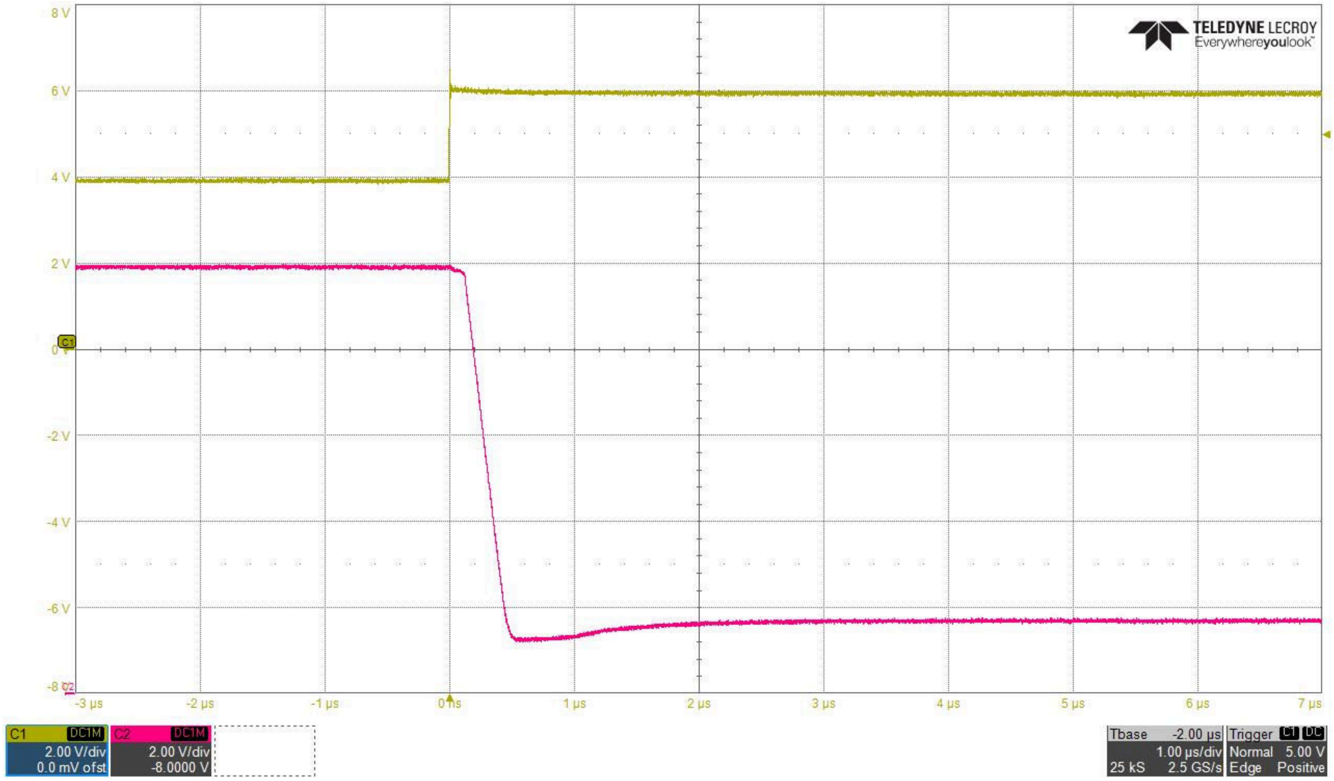


Figure 4-3. Propagation Delay (TPLH): TL431LI

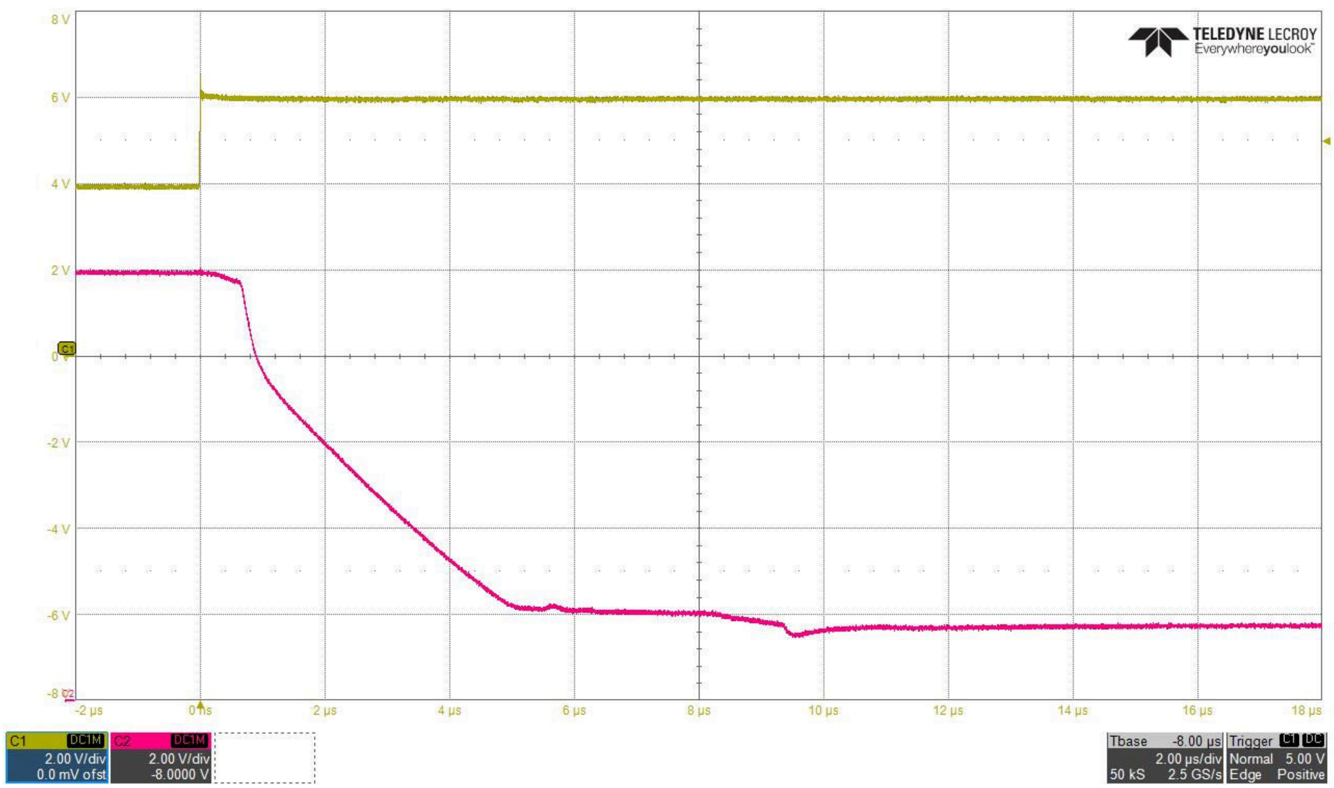


Figure 4-4. Propagation Delay (TPLH): ATL431

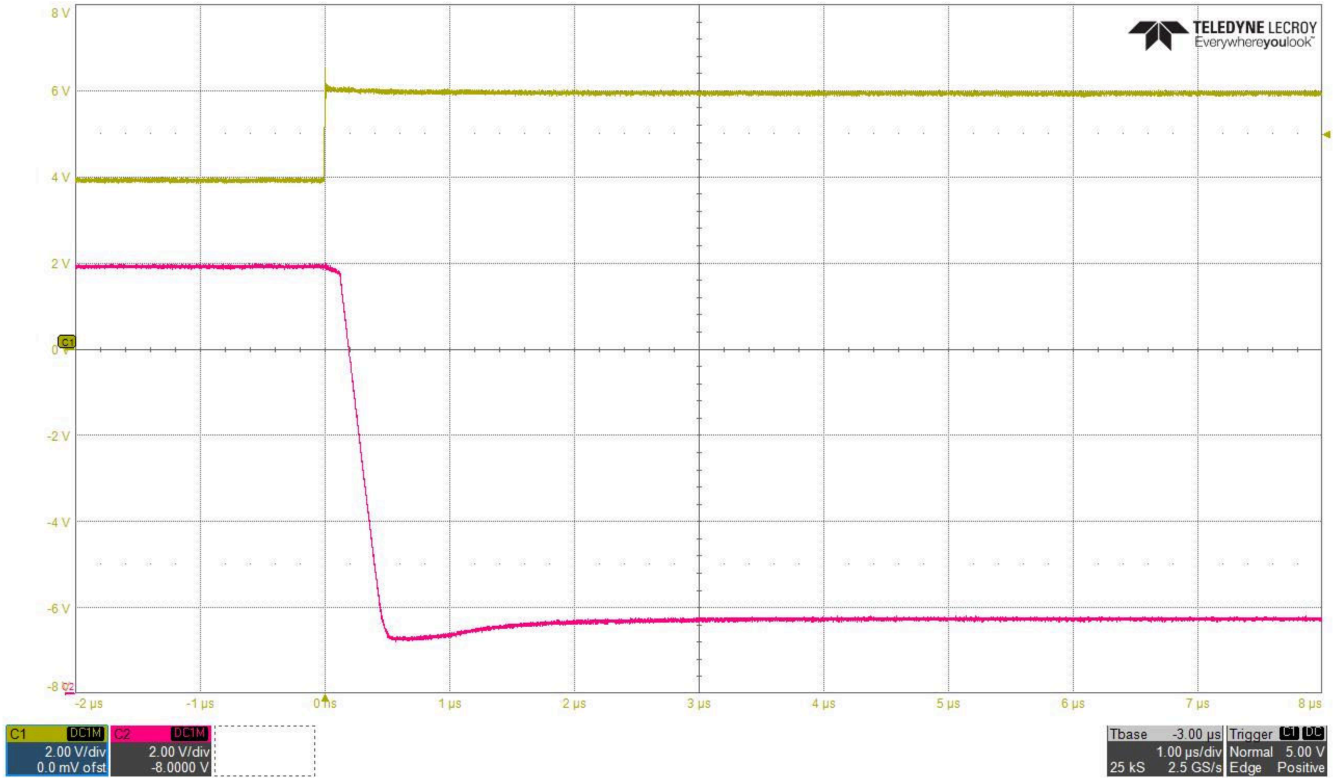


Figure 4-5. Propagation Delay (TPLH): ATL431LI

Shunt regulators from TI (TL431 , TL431, ATL431 & ATL431LI) have < 10 us typical response time and can be used for faster systems.

5 Conclusion

This application note discusses the specs of 431 devices in comparator mode and guides on selection of BOM for the comparator mode design. Stability of the output is the key challenge in the output and designers can solve the stability issue with the methods described in this application note.

6 Revision History

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

DATE	REVISION	NOTES
December 2022	*	Initial Release