Biasing the TL431 for Improved Output Impedance

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The TL431 is a well-known voltage reference integrated circuit used in Switch-Mode Power Supply (SMPS) feedback loops. Combining a reference voltage and an open-collector error amplifier, it offers advantages such as simplicity of implementation and low cost. Despite its widespread use in the industry, some designers still neglect to control the biasing current of the device with an external resistor, thereby degrading the final specification. Fig.1 shows the simplified schematic of a TL431with a reference voltage and error amplifier driving an NPN transistor.

A power supply is a closed system where a fraction of the output voltage is compared to a reference, V_{REF} in the TL431. A simplified dc model of an SMPS is a flyback topology where V_{OUT} is compared to V_{REF} via a resistive divider affected by a transfer ratio of α (Fig. 2). The theoretical voltage expected from such a configuration is simply V_{REF}/α. Unfortunately, the entire gain chain and various impedances will affect this value. Writing the output voltage definition, where each Greek letter corresponds to a gain and R_{SOL} to the open-loop output impedance:

$$V_{OUT} = (V_{REF} - \alpha V_{OUT})(\beta G - R_{SOL})V_{OUT}/RL \qquad \text{Eq. 1}$$

$$V_{OUT} = V_{REF}\beta G/(1+\alpha\beta G+R_{SOL}/RL) \qquad \text{Eq. 2}$$

The static error is defined by å, which is:

$$\mathring{a} = V_{REF}/\alpha - V_{OUT}$$

or

$$\mathring{a} = V_{REF}(R_{SOL}+RL)/\alpha(R_{SOL}+\alpha\beta GRL+RL \qquad \text{Eq. 3}$$

From Equation 3, an increase in the gain β helps reduce the static error, which eventually affects the output voltage precision. Another important parameter influenced by the gain loop is the output impedance. The output impedance of a system can be calculated in different ways. Any generator can be reduced to its Thevenin equivalent; that is, a voltage source V_{th} (V_{OUT} measured without any load—open circuit—or $R_L = \infty$ in Eq. 2), followed by an output impedance R_{th}, that can be calculated. One option consists in calculating a resistor R_L that, once wired between the output and ground, will reduce V_{th} to $V_{th}/2$. First, define a resistive divider with R_L equal to R_{th}: R_{th} is the closed-loop output impedance, also called R_{SCL}, to be found. That can be done quickly via Eq. 2, assuming $R_L = \infty$:

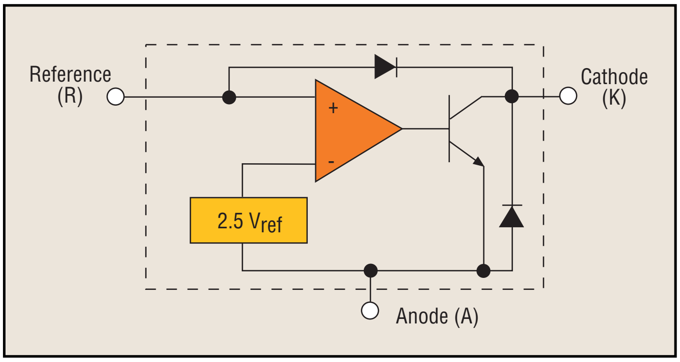

Fig. 1. *The TL431 equivalent circuit schematic.*

$V_{th}/2 = V_{OUT}(R_L)$, i.e. what value of R_L will divide the Thevenin voltage by 2?

$$V_{REF}\beta G/(1+\alpha\beta G)/2 = V_{REF}\beta G/(1+\alpha\beta G+R_{SOL}/RL)$$

$$RL = R_{SCL} = R_{SOL}/(1+\alpha\beta G) \qquad \text{Eqs. 4 \& 5}$$

Equation 5 illustrates the following:

- If the dc error amplifier gain, β_{dc} is high, then R_{SCL} is close to zero.
- Because the feedback return path β(p) is compensated, when the gain goes low with increasing frequency, R_{SCL} starts to rise. A resistance whose value increases with frequency looks like an inductance.
- When the gain, β(p), has dropped to zero, then the system exhibits the same output impedance (R_{sOL}) as when there is no feedback (i.e. system runs open-loop).

This is why most SMPS designers keep a large dc gain: first, to reduce the static error å, and second, to reduce the dynamic output impedance of the converter. Here, the dc gain will be provided by the TL431. It can be wired in a shunt regulator configuration using an NCP1200 optocoupler between the input and output stages (Fig. 3).

Assume there is no R_{bias} resistor. First, calculate the divider network resistors R_{upp} and R_{lower}. To do this, select a bridge current I_b, greater than the TL431 reference pin bias current of 6.5 µA (max) to minimize the error incurred in R_{upp} because of this bias. Choose I_b = 1 mA for an output voltage of 12 V. Since the

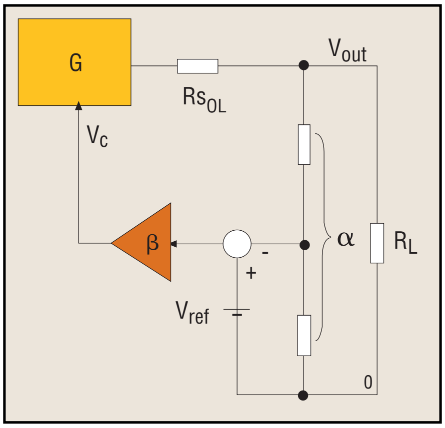

Fig. 2. *A simplified dc model for an SMPS, not accounting for the input perturbation.*

TL431 imposes 2.5 V across R_{low}, then with a 1 mA current imposed by R_{upp}, R_{low} becomes 2.5 V/1 mA = 2.5 kΩ. Then, R_{upp} simply equals 12 V– 2.5 V/1 mA = 9.5 kΩ.

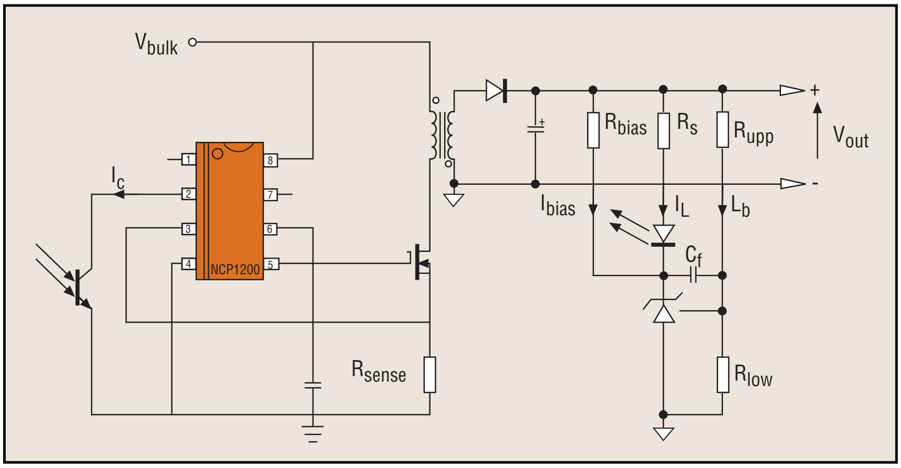

Fig. 3. *Connecting the TL431 in a traditional shunt regulator configuration.*

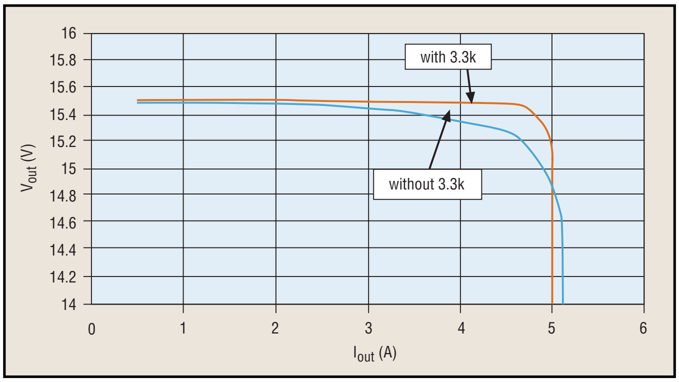

Fig. 4. *The degradation in V_{out} is clear when the TL431 biasing current is too low.*

Lower bias currents can be selected to reduce the standby power in no-load conditions. Once the bridge value is chosen, a value for R_S is next. R_S must be able to deliver enough current to bring the optocoupler collector (or the feedback pin) below 1.2 V to initiate a skip cycle in no-load operations. Inside the NCP1200 optocoupler, there is an 8-kΩ pull-up resistor from pin 2 to an internal 5 V reference voltage. If the feedback current is 475 µA to bring pin 2 to 1.2 V ($V_{pin\ 2}$ = 5 – (475 µA × 8 kΩ), then, considering a worst-case Current Transfer Ratio (CTR) of 50% for the optocoupler, Rs must be smaller than (V_{OUT} – 2.5 V– 1 V)/950 µA < 8.94 kΩ: elect it to be 8.2 kΩ. The 2.5 V comes from the fact that the minimum cathode-anode voltage cannot be lower than 2.5 V for the TL431 and there is a 1-V forward drop from the LED.

Keeping the 8.2-kΩ resistor in series with the TL431 and a CTR worst case of 150% (the opposite case of the previous one, meaning a smaller current is needed in the LED), then various scenarios can occur:

- Light load conditions: I_{FB} = 475 µA, then I_L = 475 µA/ 1.5 = 316 µA.
- Moderate load conditions, V_{FB} = 2.3 V, I_{FB} = 337.5 µA, then I_L = 337.5 µA/1.5 = 225 µA.
- Heavy load conditions, V_{FB} = 3 V, I_{FB} = 250 µA, then I_L = 250 µA / 1.5 = 166 µA.

This shows that the biasing current of the TL431 not only varies with the load current, but also with the optocoupler CTR. And there is nothing to be gained by reducing R_s, because what matters is the current inside the LED to fix the right feedback voltage on the controller side. The design issue in this case, comes from the TL431 datasheet: You must inject more than a 1-mA biasing current to benefit from different guaranteed specs among which is the TL431 gain. If the TL431 is not properly biased, it will degrade the open-loop gain β of the previous equations: å increases and R_{SCL} increases.

Fortunately, a bias current can be imposed externally via the resistor R_{bias}. This resistor will be calculated in the worse case; that it to say at high load (and highest CTR) as exemplified by scenario 3 because the lack of current there is largest. In this situation, I_L = 166 µA. Therefore, 166 µA (8.2 k) = 1.36 V is dropped over R_S.

If 1 V is the LED forward drop, then the cathode voltage will be: 12 – 1.36 – 1 = 9.64 V. Knowing that V_{OUT} is constant at 12 V, then imposing a 1-mA current via R_{bias} will lead to R_{bias} = (12 – 9.64) / 1 mA = 2.36 kΩ or 2.2 kΩ for a normalized value.

Therefore, impose a minimum current of 1 mA + 166 uA = 1.16 mA in the TL431. Under no-load conditions, the 316 µA of scenario 1 forces a 12 – (8.2 kΩ × 316 µA) – 1 = 8.4 V on the cathode, which leads to a total bias current flowing inside the TL431 of (12 – 8.4)/2.2 k = 1.63 mA plus the actual feedback current of 316 µA, which comes to 1.95 mA. This should be a safe value.

An experiment has been carried on a power supply built with a NCP1200 with and without the biasing resistor (here a 3.3 kΩ). Fig. 4 shows the effects of the resistor.

In the first case, without biasing element, the output impedance was measured to be 57 mΩ. By connecting the bias resistor, that value dropped to 4 mΩ.

In conclusion, do not forget to properly bias the TL431 via an external resistor. If an extra 1 mA is too high on the output (because the no-load standby power should be minimized), choose a TLV431 (V_{REF} = 1.24 V) or a NCP100 (V_{REF} = 0.7 V), because they only require a minimum bias current of 100 µA but exhibit lower breakdown voltages. Also, a series resistor R_S of 8.2 kΩ is rare because this resistor combines with the optocoupler collector pull-up resistor to form a dc gain. Values around 1 kΩ or slightly higher are more typical values. **PETech**