

Designing with the TL431

by Dr. Ray Ridley

Designer Series XV

Power supplies are constantly striving to reduce cost. Prices are now being driven down to insanely low levels, and compromises must often be made to meet performance and cost goals.

One of the targets for cost reduction is always the control loop. Designers are often so focused on power processing that control design is often an afterthought, and not viewed as crucial to performance. Only later in the design process does the importance of a good controller become apparent.

One of the early ways to reduce the cost of the feedback loop was to utilize the TL431 controller. While not offering as good a gain-bandwidth as a standalone amplifier, this three-terminal part includes a reference, takes up little board space, and became widespread in the industry as a way to achieve reasonable performance at a reduced cost.

In this designer series article, we'll look at the complications involved in using the TL431, especially when it is configured with an optocoupler to provide isolation in the feedback loop.

1. Operational Amplifier Feedback

For the best performance, the preferred approach to feedback control compensation is an error amplifier and a precision reference. For nonisolated converters, the amplifier and reference may be included in the PWM control chip, and they are usually of sufficient quality to meet demanding standards.

Current-mode control is the best way to control converters, and is used by most power supply designers. For this type of control, the optimal compensation network is a Type II amplifier, an example of which is shown in Figure 1. In this configuration, a conventional operational amplifier is used to amplify the difference between the output voltage of the power supply and a fixed reference voltage.

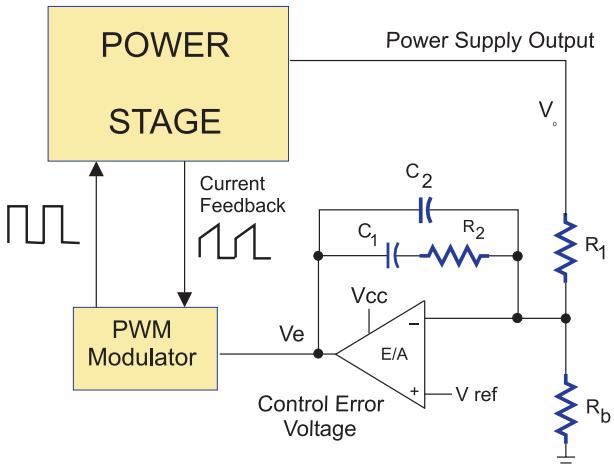


Figure 1a: Type II Compensation Feedback

The amplifier is supplied by a separate V_{cc} , and the operation is not affected by variations in the supply voltage due to good power supply rejection ratio.

Figure 1b shows the typical compensation curve for a Type II amplifier. At low frequencies, the circuit acts like an integrator, utilizing components C_1 and R_1 to provide high gain. Resistor R_b provides the correct dc regulation level, but due to the virtual ground at the input of the error amplifier, it does not appear in any of the gain equations.

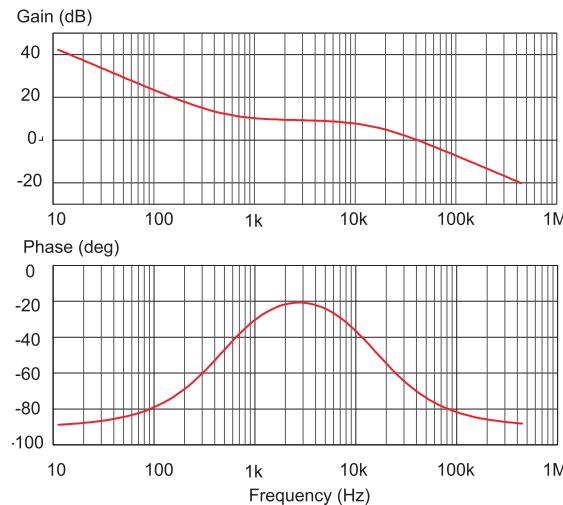


Figure 1b: Type II Compensation Bode Plot

At a frequency typically several times less than the loop gain crossover, a zero is introduced in the transfer function, and the midband gain of the compensator is a simple expression given by the ratio of R_2 and R_1 .

At a higher frequency, selected according to the power stage characteristics, the circuit again forms an integrator, the gain determined by R_1 and C_2 . Exact choice of these parameters are outside the scope of this design article, but can be found in the literature. (If you want to learn this thoroughly, come to our course in Alpharetta, Georgia for a four-day intensive lab workshop.)

Many engineers have asked over the years, "When are you going to do the TL431 in the POWER 4-5-6 design software?" At first, I was a little puzzled by this, since it seemed to me that there was no difference in whether you use the TL431, or a discrete operational amplifier and reference. Since I was involved in the design of high performance power supplies at the time, it didn't make any sense to me to use a lower performance part than the best amplifiers that were available.

Figure 2 shows how the TL431 can be used as a standard error amplifier. There are three differences found when using this part versus a standard operational amplifier:

1. *A pullup resistor must be used on the output.*
The value of this resistor must be chosen to provide sufficient bias current to the device under all circuit conditions. Furthermore, the output of the amplifier must be kept above a minimum value required to provide the bias.
2. *The reference is included in the part. It's actually a pretty good reference.*
3. *The open loop gain, and drive capability are less than that of a good op amp. However, if you keep the impedances around the amplifier high, it will work well.*

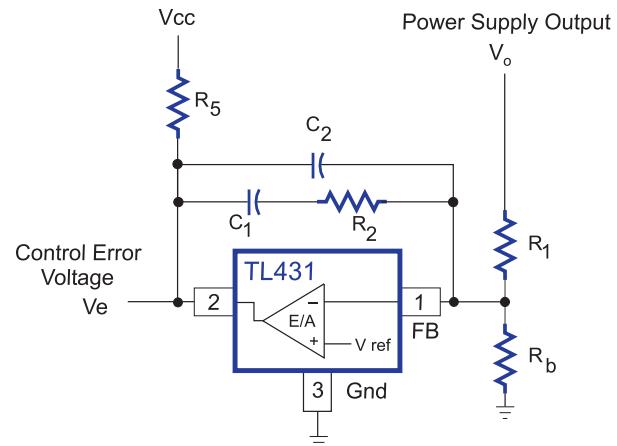


Figure 2: TL431 Used as a Type II Amplifier

If the TL431 is configured as shown in Figure 2, and the rules above are obeyed, the design procedure is exactly the same as for a standard Type II amplifier.

2. TL431 Solution with Isolation

When engineers have asked this question about the TL431, they don't usually refer to its operation as shown above in Figure 2. They are talking about the circuit that has become very widespread in the industry where the TL431 is used in conjunction with an optocoupler to provide feedback loop isolation, as shown in Figure 3.

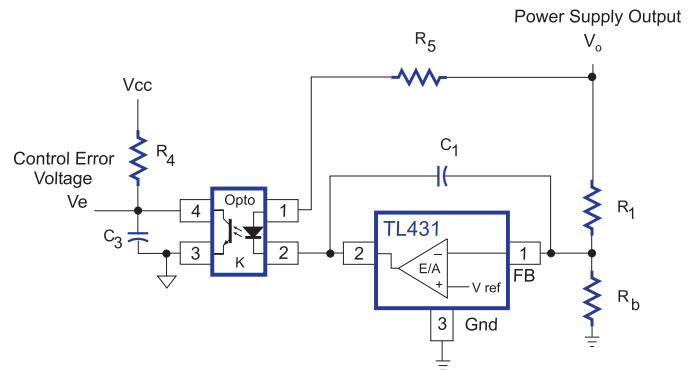


Figure 3: Typical TL431 Configuration with Output Bias and Optocoupler

In this circuit, the output of the TL431 is powered through the resistor, R_5 , and the optocoupler diode, connected in series with the power supply output. This apparently subtle change has a big effect on the way the circuit works. The biggest change is that the gain of the circuit is now driven by the current into the output of the TL431, not by its output voltage. This current is determined by three things: the voltage gain of the TL431, the supply voltage to the top of the resistor R_5 , and the value of the resistor itself. The circuit of

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Figure 2 is independent of the resistor value and the supply voltage. The circuit of Figure 3 is a strong function of both of these quantities.

Note that the compensation shown around the TL431 consists of just a capacitor, C_1 . A second capacitor, C_3 , represents the output capacitance of the optocoupler, and its frequency response rolloff. However, the circuit of Figure 3 is still a type II compensator, although this is not immediately apparent.

3. TL431 Compensation - Low Frequency

At low frequencies, the gain of the TL431 amplifier, with capacitor C_1 and Resistor R_1 forming an integrator, is high, and this dominates the response. Figure 4a shows the low-frequency equivalent circuit.

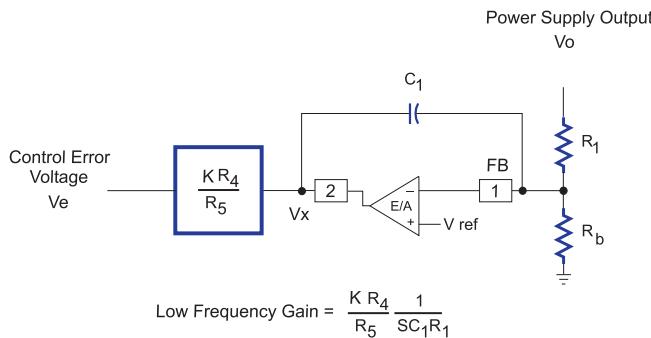


Figure 4a: Low Frequency Circuit for Typical TL431 Connection

The gain from the power supply output to the output of the error amplifier, V_x , is given by the classic integrator equation, and plotted in green in Figure 4b. Going across the isolation boundary through the optocoupler, this integrator gain is multiplied by the current gain of the optocoupler, and the ratio of the resistors R_4 and R_5 . The net low frequency gain of the circuit, from power supply output, to control input, V_e , is shown in blue in Figure 4b.

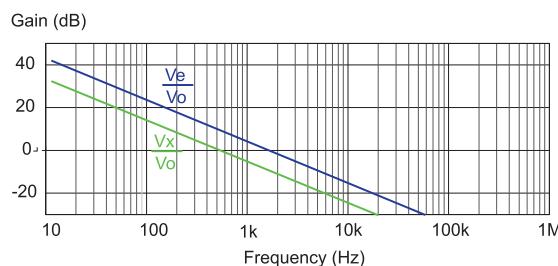


Figure 4b: Low Frequency Gain of Typical TL431 Circuit

4. TL431 Compensation - Mid Frequency

At a higher frequency, the gain of the integrator around the TL431 amplifier reaches unity, and beyond this point, the output signal is attenuated. However, there is always gain from the output voltage to optocoupler diode current due to the connection of the resistor R_5 to the power supply output. In the midband frequencies, this is the dominant feedback path.

Figure 5 shows the equivalent circuit in the midband region. The gain is determined entirely by the choice of resistors on the primary and secondary side of the optocoupler, and the amplifier is not a part of the circuit. The crossover of the loop will normally occur during this frequency range, and the resistors should be the first part of the design of the circuit to make sure that the desired crossover frequency is achieved.

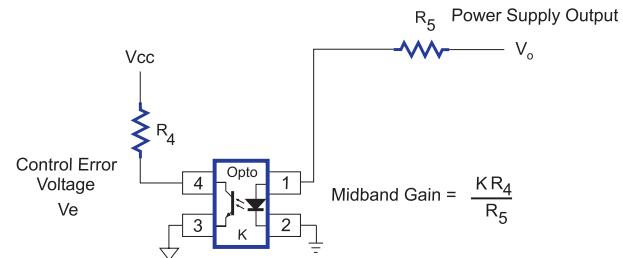


Figure 5: TL431 Circuit Midband Gain

5. TL431 Compensation - High Frequency

At high frequencies, we encounter the pole of the optocoupler itself. This is represented by the capacitor C_3 in the circuit of Figure 6a.

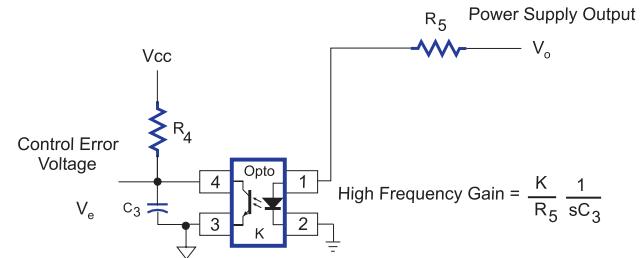


Figure 6a: TL431 High Frequency Gain Circuit

Figure 6b shows the rolloff of the gain of the optocoupler. With a good optocoupler, this can be a high frequency, in excess of 10 kHz. However, the rolloff is a function of the current level at which the optocoupler is operated. The more current flowing in the device, the higher the bandwidth. It is advisable to bias the optocoupler with relatively low values of resistors to make sure it operates near the upper end of its rated current range. This will give the maximum bandwidth of the device.

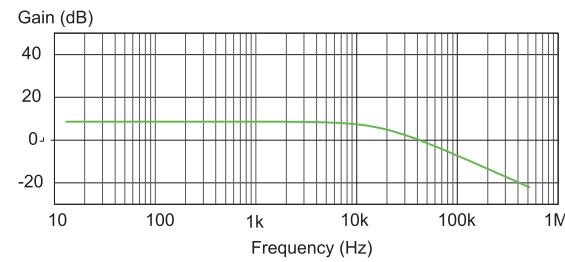


Figure 6b: Mid-Frequency and High-Frequency Gain Plot

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Unfortunately, for many integrated power supplies, the bias resistor is built into the controller, and cannot be easily changed. This often forces the optocoupler to operate in the low current region, and the loop design is compromised.

6. TL431 Complete Compensation

The two feedback paths of the TL431 configuration combine to give the total compensation as shown in Figure 7. The integrator gain, shown in blue, dominates at low frequencies, and the second feedback path through the bias resistor dominates at mid and high frequencies.

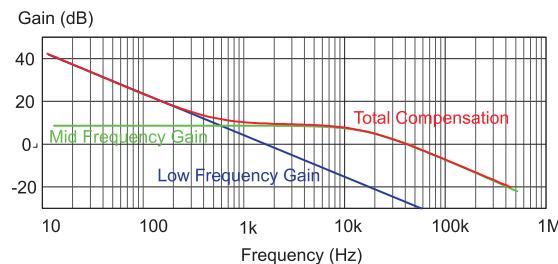


Figure 7: TL431 Final Compensation Gain

The resulting total compensation is shown in red. This is still the desired Type II compensation, optimal for current-mode control. However, the design of the frequency break points is now more complex, and determined by components other than just the feedback parts around the error amplifier. The important design features are:

1. *The midband gain determines the crossover frequency. This depends on the resistors R_4 and R_5 , and the optocoupler current transfer ratio. These components should be chosen first in designing the loop.*
2. *Compensation zero. This occurs when the gain of the integrator, formed by R_1 and C_1 , is unity. We normally put this zero at about one-third the crossover frequency of the control loop.*
3. *High-frequency pole. This is determined by the optocoupler characteristic and bias point. We normally strive to make this as high as possible.*

I have seen numerous power supply circuits that use the TL431 as just a zener diode, without taking advantage of the amplifier for low frequency gain. This is almost always done because the designer does not understand the complex interactions of the different loops, and does not have access to frequency response measurement equipment to confirm a stable design. The penalty is a very poor transient response, and poor dc regulation. It only cost a few cents to take advantage of the TL431 amplifier properly, but of course it takes better development engineering skills.

7. TL431 Loop Measurement

The TL431, when used as an error amplifier as shown in Figure 2, is actually a surprisingly good part, at a very affordable price. When used in its normal isolating configuration, as shown in Figure 3, it is still a very good component,

but the loop is dominated at all frequencies by the response of the optocoupler.

If you are going to use this circuit for compensation, (and a large percentage of commercial supplies do), you MUST, repeat, MUST, measure the resulting loop gain to make sure you have a ruggedly stable system. The entire stability of your power system using the TL431 circuit is dependent upon quantities that can be very variable. The gain and bandwidth of the optocoupler can change from part to part, and also vary significantly with time and temperature.

Care must be taken in measuring the loop. It is important that you break *both* of the feedback paths by injecting as shown in Figure 8. This will provide the proper loop gain of the system. If you attempt to measure the loop at either point A or B shown in this figure, the measurement results will not be particularly useful for the design of a well-compensated loop.

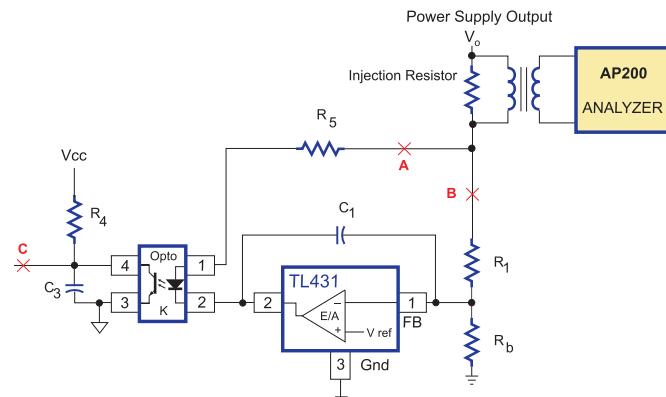


Figure 8: TL431 Loop Measurement Points

An additional valid point for injection and measurement is at point C, on the primary side of the isolation boundary, although this is sometimes more difficult to implement due to the line-referenced voltages.

8. TL431 with Second Stage Filter

One final point about using the TL431 circuit: In some applications, a second-stage filter is needed to produce a low-noise output of the supply, as shown in Figure 9a. In this configuration, one feedback loop is closed via R_5 from the left of the second-stage filter inductor, and the other feedback loop through the integrator from the right of the filter inductor, and the output of the power supply.

This is a very interesting and useful circuit. As long as the second stage filter resonance is properly damped, and its frequency is placed well beyond the first zero of the TL431 compensation, the circuit will be stable. The bode plot of Figure 9b clearly shows why. The extra phase delay and poles of the second-stage filter show up directly in the loop through the integrator, but this does not determine the loop response when the gain of the integrator is less than unity—beyond the zero of the overall compensation.

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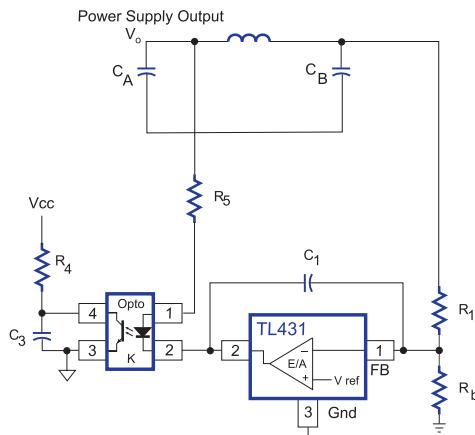


Figure 9a: Typical TL431 Configuration with Second-Stage Filter

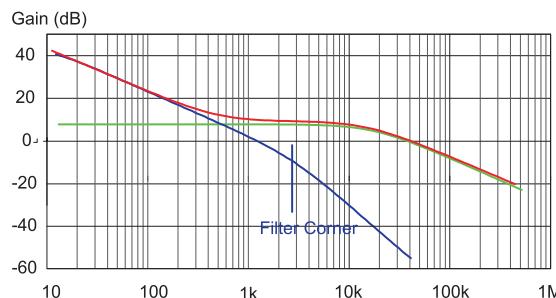


Figure 9b: Effect of Second-Stage Filter on Compensation Gain

There will be a perturbation (not shown) in the other feedback loop which will depend on the damping of the second stage filter, but the phase will return to the same level as without the filter.

The second stage filter also presents a complication in measuring the loop gain. We can no longer identify a good loop injection point at the output of the power supply. Injecting on the other side of the optocoupler (at point C in figure 8) is one option, but this is usually on a high voltage primary, and is more difficult to measure. If you cannot inject on the primary side, the best approach is to short circuit the second filter inductor, measure the loop as shown in Figure 8, and make sure you design the second stage resonant frequency beyond the unity gain point of the integrator.

Summary

Should you use the TL431 as your primary feedback amplifier? By all means, it has a good internal amplifier, and reference, and if your output voltage level is high enough, it can be made to work well. (A low voltage version of the part, the TLV431, extends the range of operation to lower output voltages.) If you hook the TL431 up in its industry standard configuration with an optocoupler, just be sure to follow the recommendations of this article, and you should be able to design a good rugged control loop.

Just to reiterate—make sure you measure the loop that you design - there are too many loosely controlled variables in the power supply and feedback loop to leave this to chance. It is also important to thoroughly understand how each of the feedback components affects the compensation of the system.

There is a sample version of POWER 4-5-6 that you can download for free at

<http://www.onsemi.com/site/support/models>.

The download includes a detailed model of the TL431 implemented with optocouplers. The compensation page lets you change component values, and interactively see the change in the loop gain. This is a very useful exercise to develop a better understanding of this control circuit.