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Using the TL431 in a Power Supply

I've devoted several articles so far to the complexities of allegedly simple passive components. In this article, we'll look at one of the active semiconductors of the power system—the popular TL431. This three-terminal part includes a precise voltage reference and an amplifier. It consumes very little board space and is widely used in the industry to achieve reasonable performance at low cost. However, its analysis is very complex when used with an optocoupler for feedback isolation.

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Operational Amplifier Feedback

For the best performance, the preferred circuit for feedback control compensation uses an error amplifier and a precision reference—part of the control chip for non-isolated supplies. 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

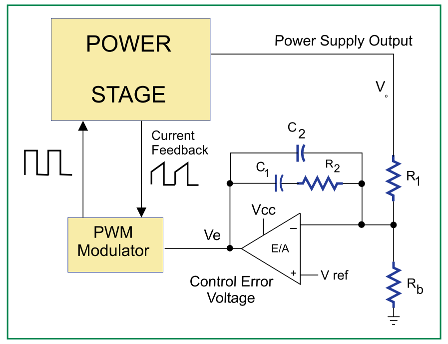


Figure 1a: Type II Compensation Feedback.

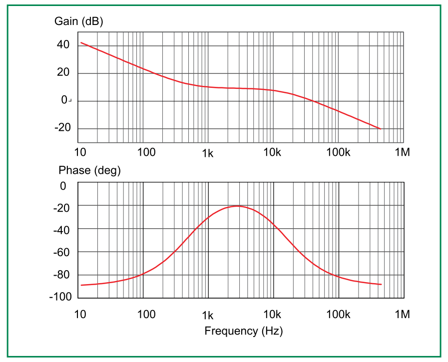


Figure 1b: Type II Compensation Bode Plot.

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 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.

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 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 R1 and C_2. Exact choice of these parameters are outside the scope of this article [1,2].

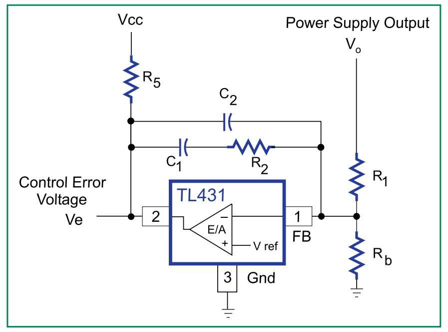


Figure 2: TL431 Used as a Type II Amplifier.

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. A good voltage reference is included in the part; and
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.

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

TL431 Feedback with Isolation

Most engineers using the TL431 don't use it as in Figure 2. They use 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.

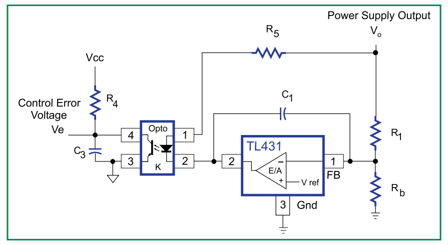


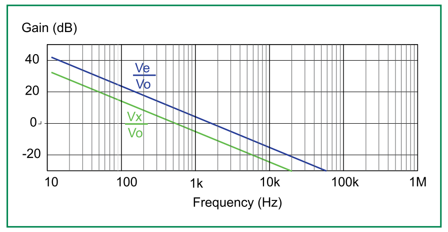
Figure 3: Typical TL431 Configuration with Output Bias and Optocoupler.

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 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. While the circuit of 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 feedback compensation 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.

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.



The gain from the power supply output to the output of the error amplifier, Vx, 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 resulting low frequency gain of the circuit, from power supply output, to control input, Ve, is shown in red in Figure 4b.

TL431 Compensation – Mid Frequency

At a higher frequency, the gain of the integrator around the TL431 amplifier reaches unity, and beyond this point, the voltage 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 part of the circuit. The crossover of the loop will normally occur during this frequency range, and the resistors should designed first for the desired crossover frequency.

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 6b shows the rolloff of the gain of the optocoupler. With a good opto-

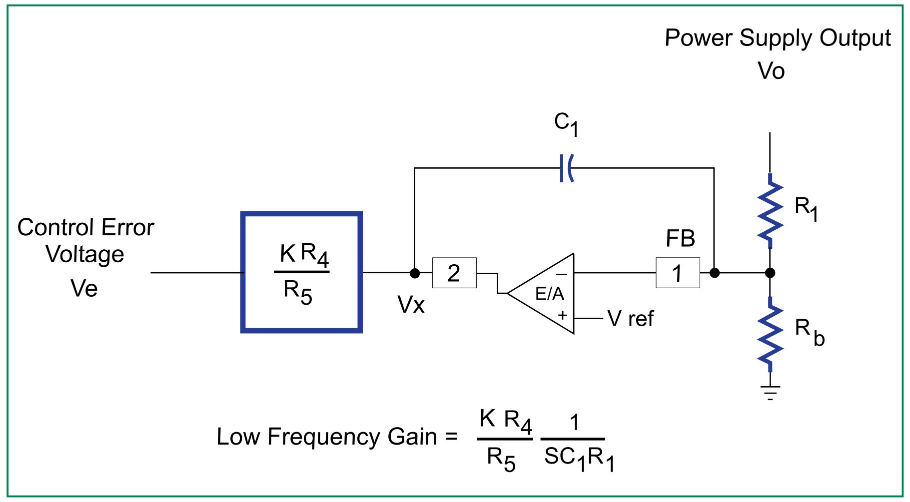


Figure 4a: Low Frequency Circuit for Typical TL431 Connection.

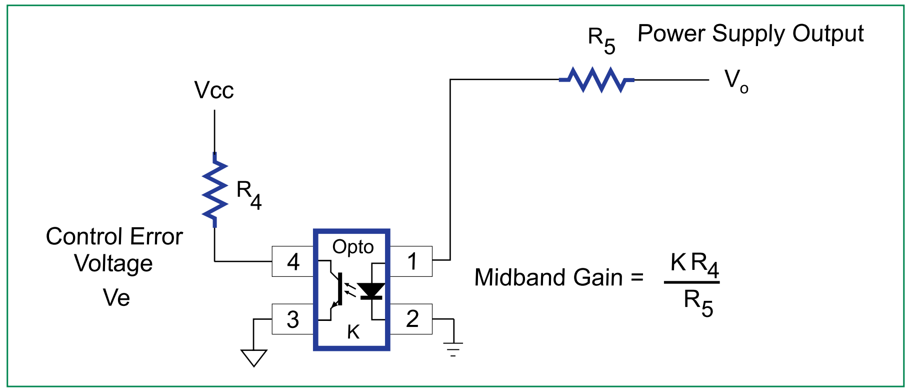


Figure 5: TL431 Circuit Midband Gain.

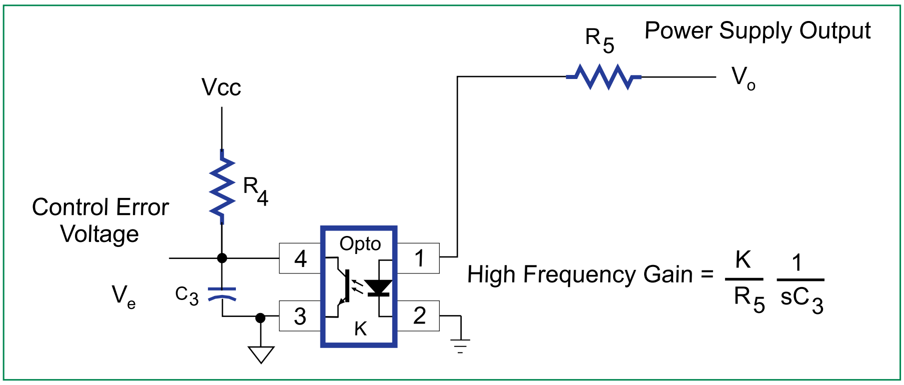


Figure 6a: TL431 High Frequency Gain Circuit.

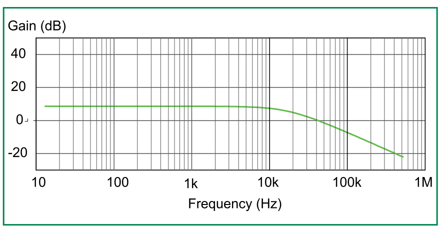


Figure 6b: Mid-Frequency and High-Frequency Gain Plot.

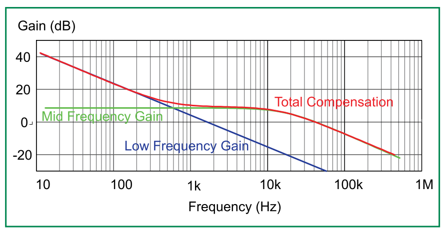


Figure 7: TL431 Final Compensation Gain.

coupler, this can be 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.

Unfortunately, for 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.

TL431 Complete Compensation

The two feedback paths of the TL431 configuration combine to give the total compensation 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.

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.

TL431 Loop Measurement

If you are going to use this circuit for compensation, you MUST measure the resulting loop gain to make sure you have a 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.

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 line-referenced voltages.

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 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, be sure to follow the recommendations of this article, and you should be able to design a rugged control loop.

1. Design course notes, www.ridley-engineering.com/workshop.htm
2. "Switch Mode Power Supply SPICE Simulations and Practical Design", Christophe Basso.

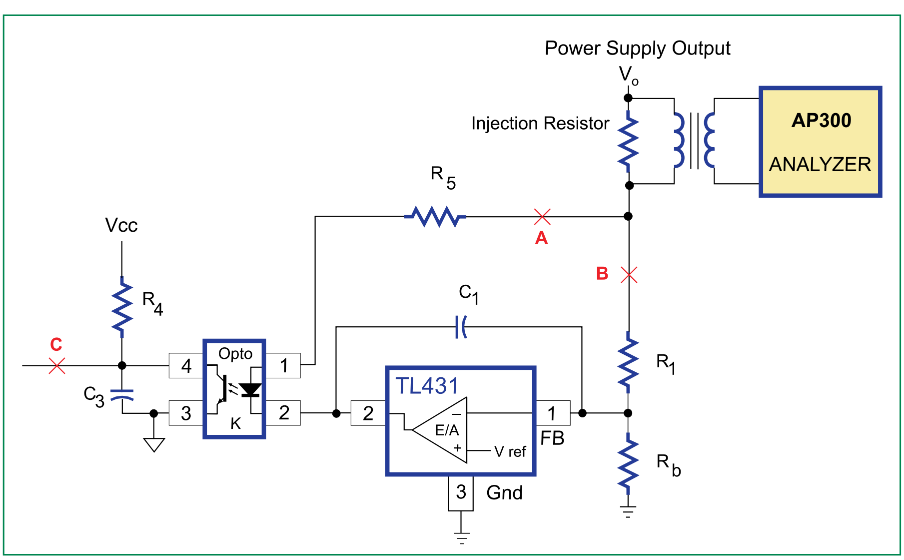


Figure 8: While measuring the loop, it is important to break both of the feedback paths by injecting.

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