Using Cascodes with the TL1451

Peter James Miller   *System Power*

ABSTRACT

The TL1451 is a low cost, dual PWM controller with open collector sink only outputs designed to drive a discrete drive stage for low cost power converters. When used in a BUCK configuration, the TL1451 typically drives a P-channel MOSFET switch. When configured like this, the TL1451's output must withstand the full V_{IN} voltage. In some applications it is desirable, if not necessary, to have a V_{IN} greater than the TL1451's maximum voltage of 50 V. In such applications a cascode transistor is used to protect the TL1451 from the high V_{IN} voltage while retaining control of the circuit. In conventional cascode circuits an external reference is used to drive the cascode. This paper discusses a circuit topology that allows the TL1451 to have this protection with fewer parts, reducing part count, system cost and PCB space.

1   The Cascode

The theory of the cascode transistor is quite simple. A high voltage transistor is placed in series with a lower voltage control transistor to provide increased protection to the smaller control transistor. A typical NPN cascode pair is shown in Figure 1.
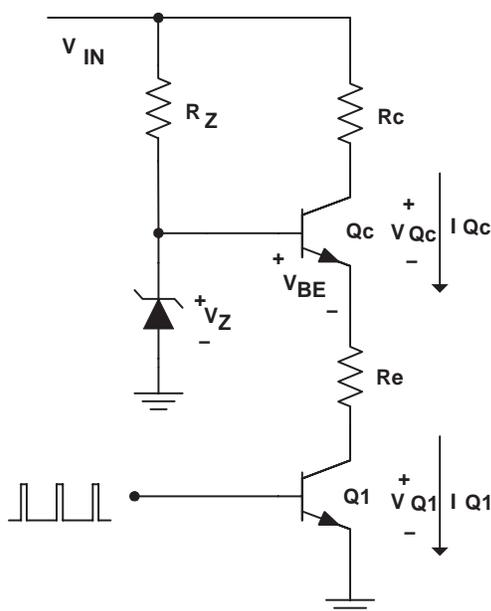

Figure 1. An NPN Transistor With Cascode

In Figure 1, Q1 is controlled by the pulse train fed into its base. When Q1 turns *ON* it sinks I_{Q1} from the emitter of the cascode transistor Qc. If V_{IN} is sufficient to prevent Qc from saturating, $I_{Qc} = I_{Q1}$, thus allowing Q1 to control the current in Rc as if the cascode transistor wasn't there.

When Q1 is *OFF* $I_{Q1} = I_{Qc} = 0$. With no current through Rc, the voltage at the collector of Qc is V_{IN}, however the voltage at the collector of Q1 is equal to V_Z since V_{BE} must equal zero for $I_{Qc} = 0$.

As a result, $V_{Qc} = V_{IN} - V_Z$ and $V_{Q1} = V_Z$. This allows Q1 to have a maximum voltage well below V_{IN} as would be required without the cascode. This allows a fairly small, low voltage transistor to control a system with a very high V_{IN} voltage.

2 A Cascode On an Open Collector Output

An open collector output is typically little more than a ground referenced sink transistor such as a NPN bipolar junction transistor (BJT) or N-channel MOSFET. If the control transistor (Q1) in the previous circuit is replaced with the open collector output of a device, the open collector output controls the cascode transistor (Qc). This allows the device to operate in a system where V_{IN} is greater than the device's output voltage rating.

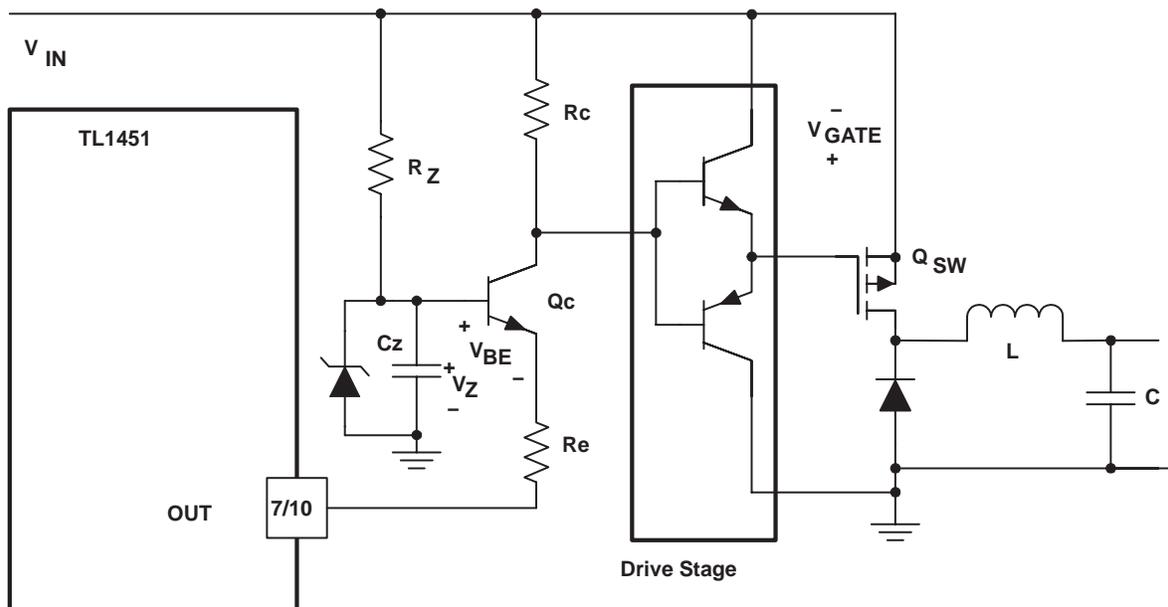Figure 2 shows the TL1451 dual output controller with a cascode transistor on its output.

Figure 2. TL1451 With Cascode Transistor

As long as V_Z is less than 50 V the TL1451's output is protected from high V_{IN} voltages and Qc's voltage rating determines the maximum allowable V_{IN} while V_Z determines the minimum V_{IN}. This configuration allows the TL1451 to be used with much higher input voltages than could be realized without the cascode transistor; however this technique requires a pass resistor, zener diode and filtering capacitors. It is possible in some applications to use the TL1451's 2.5-V reference to drive the base of Qc, thus eliminating the need for these additional components.

3   Cascode Output with V$_{REF}$ base drive

By using the TL1451's available 2.5-V reference to drive the base of the cascode transistor, it is possible to eliminate the additional zener diode, resistor and filtering capacitor from the cascode circuit. This technique fixes $V_Z = V_{REF} = 2.5$ V and can be used even when V_{IN} requires a minimum voltage below 10 V.
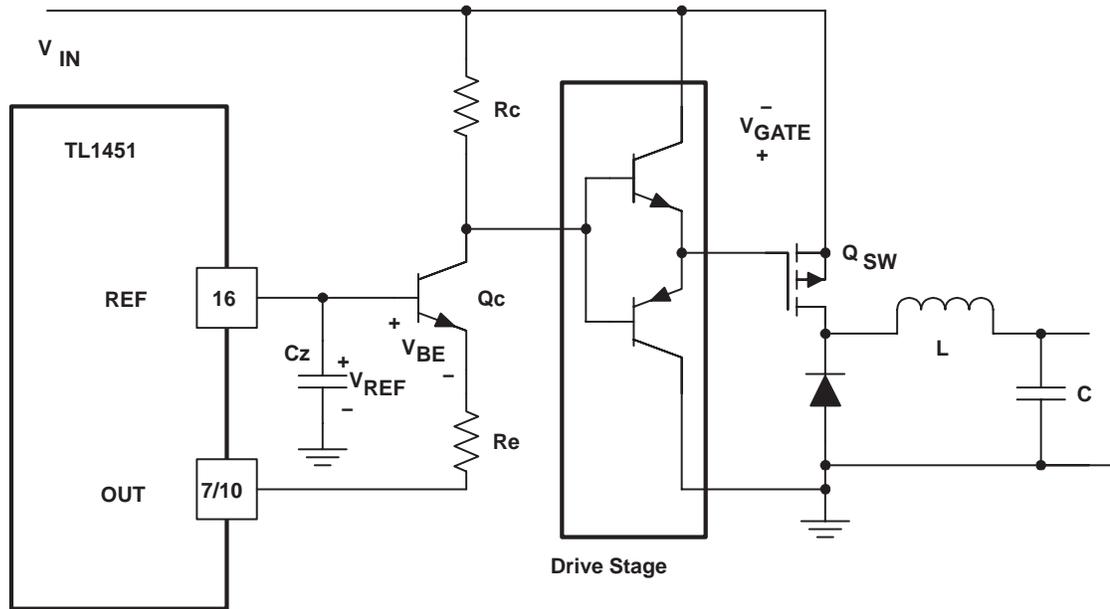

Figure 3. TL1451 With Cascode Using V$_{REF}$ Base Drive

In Figure 3, Qc receives its base voltage from the TL1451's REF pin (pin 16) eliminating the need for the resistor and zener diode. Additionally, the same bypass capacitor normally used on this pin can serve as the filtering capacitor for the base drive.

This technique is not without its limitations, the low value of V_{REF} requires Qc to handle all of V_{IN}, requiring a larger cascode transistor than might be otherwise necessary. Also, the low value of V_{REF} severely limits the voltage drop V_{Re}, requiring a larger Re to Rc ratio and increasing the dependency of V_{Re} on thermal variations in V_{BE}. Additionally, Qc must have sufficient current gain (β) to minimize the current draw from V_{REF}, reducing the available selection of cascode transistors. Within these limitations the ability to drive a cascode transistor with the TL1451's reference voltage can reduce the cost and board area requirements of many high voltage or wide input range converters utilizing the TL1451 controller.

4 Designing a TL1451 Cascode

When designing an output cascode circuit, several things must be considered. First, a cascode circuit adds components, cost, board area and power loss to a circuit and should only be used when system specifications require. This normally occurs when the input voltage exceeds the maximum operational voltage of the controller, 50 V in the case of the TL1451, or when additional derating is required.

Once it is determined that a cascode circuit is required, the following values are necessary to design the cascode effectively.

- Maximum input voltage ($V_{IN(max)}$)

- Minimum input voltage ($V_{IN(min)}$)

- Desired gate drive voltage (V_{GATE})

- Minimum gate drive voltage ($V_{GATE(min)}$)

- Switching frequency (f_{SW})

These values are used to determine the required specifications for Qc, Re and Rc. The example uses a 5-V output, 10-V to 50-V input, 100-kHz switching frequency with a logic level MOSFET that can drive at 8 V, but allowing as little as 7 V and still getting acceptable performance.

4.1 Selecting V_Z

If the cascode transistor (Qc) is to use the TL1451's reference voltage (V_{REF}) to drive its base voltage, V_Z is fixed at 2.5 V. If an external zener diode is used to set V_Z, it must be selected within reasonable bounds.

First, the TL1451's output sees V_Z during its *OFF* time, setting the maximum possible voltage at 50 V, however this is only practical with very high V_{IN} supplies. Second, V_{Rc} sets the gate drive to the P-channel MOSFET, and since V_{Rc} is determined by:

$$V_{Rc(max)} < V_{IN} - V_Z$$

V_Z is bounded by:

$$V_{Z(max)} < V_{IN(min)} - V_{GATE(min)}$$

If this produces a $V_{Z(max)}$ value of less than 2.5 V a lower threshold MOSFET or higher $V_{IN(min)}$ should be selected as the available V_{Re} voltage is too low and thermal variation in V_{BE} of the cascode transistor poses a significant problem. If $V_{Z(min)}$ is between 2.5 V and 10 V, one should strongly consider the advantages of using the TL1451's available reference to supply the base drive to the cascode transistor.

For this example, $V_{IN(min)}$ = 10 V and $V_{GATE(min)}$ = 7 V so:

$$V_{Z(max)} < 10\ V - 7\ V = 3\ V$$

Since $V_{Z(max)}$ is very close to 2.5 V, use the TL1451's reference to drive the cascode transistor, setting V_Z = 2.5 V.

4.2   Selecting Re and Rc

Re and Rc are selected to control the sink current of the TL1451's output transistor and regulate the gate drive voltage supplied to the MOSFET. Since the output controls a descrete drive stage as in Figure 2 and Figure 3, Re should be sized to limit the sink current to 10 mA or less. V_{Re} is given by :

$$V_{Re} = V_Z - (V_{BE} + V_{SAT})$$

Since using the TL1451's reference voltage, V_Z = 2.5 V, V_{BE} = 700 mV and V_{SAT} = 1 V, so

$$V_{Re} = 2.5\ V - (0.7\ V + 1\ V) = 800\ mV$$

$$Re > \frac{V_{Re}}{I_{SAT}} = \frac{800\ mV}{10\ mA} = 80\ \Omega$$

This means Re should be greater than 80 Ω. Use a 100-Ω resistor for the rest of this example.

$$I_{SAT} = \frac{V_{Re}}{Re} = 8\ mA$$

Rc should be selected to provide V_{GATE} when Ic = I_{SAT}.

$$Rc = \frac{V_{GATE}}{I_{SAT}}$$

For this example, use 8 V of gate drive voltage, then select:

$$Rc = \frac{8\ V}{8\ mA} = 1\ k\Omega$$

4.3 Selecting a Cascode Transistor

The key specifications for Qc are collector-emitter breakdown voltage, current rating, base-emitter current gain or beta, saturation voltage and base emitter forward voltage drop.

4.3.1 Break-Down Voltage

The collector-emitter voltages during the *OFF* time is given by:

$$V_{CE} = V_{IN} - V_Z$$

So, in most designs, the collector emitter breakdown voltage should be greater than $V_{IN(max)}$, however the cascode should never see a voltage greater than $V_{IN(max)} - V_Z$, so lower voltage transistors can be used to reduce system cost for higher voltage applications.

4.3.2 Emitter Current/Power Dissipation

With the breakdown voltage selected, it is necessary to choose a transistor capable of carrying I_{SAT} as calculated earlier. While nearly any transistor is able to carry the 10 mA typically designed for, the power dissipation in this device can be troublesome, especially in higher voltage systems. Because of this, the power dissipated in the cascode transistor needs to be calculated.

The power is made of two components, the switching losses (P_{SW}) and the conduction losses (P_{CON}) and they are estimated as follows:

$$P_{SW} = \frac{1}{3}\left(I_{SAT} \times V_{IN(max)} \times T_{SW} \times f\right)$$

and

$$P_{CON} = I_{SAT} \times \left(V_{IN(max)} - V_Z\right) \times \frac{V_{OUT}}{V_{IN(max)}}$$

Where T_{SW} is the total switch time of Qc given by the sum of the turn-on time and the turn-off time.

Since the exact switch time can be fairly involved to calculate, over estimate the switch time at 250 ns per transition for a T_{SW} of 500 ns. At a switching frequency of 100 kHz:

$$P_{SW} = \frac{1}{3} \times 8 \; mA \times (50 \; V) \times 500 \; ns \times 100 \; kHz = 6.7 \; mW$$

And a conduction loss of:

$$P_{CON} = 8 \; mA \times (50 \; V - 2.5 \; V) \times \frac{5 \; V}{50 \; V} = 38 \; mA$$

Therefore the cascode transistor must be able to dissipate 45 mW of power during normal operation and should probably be selected to handle at least twice that amount to maintain a lower junction temperature

4.3.3   Current Gain

Current gain, or beta (β)of the transistor should be selected to minimize the current draw on the base supply voltage. Most low current, small signal transistors have fairly high current gain, typically between 100 and 300. This is sufficient to minimize draw on the reference voltage, but care does need to be taken not to select a power transistor which could have a significantly lower beta value.

4.3.4   Base-Emitter Voltage Drop

In the above example an assumed base emitter voltage of 700 mV was used, as this is the most common typical value for small signal transistors, but at this point it may be necessary to reevaluate some of the previously selected values, specifically Re and Rc to accommodate different forward voltage drops. Using the current gain (β) and saturation current (I_{SAT}) calculate the base current as:

$$I_B = \frac{I_{SAT}}{\beta}$$

This can be compared to the I_B/V_{Be} curve of the specific transistor selected and the actual V_{Be} can be determined and used to make any necessary adjustments in the Re and Rc values.

As with any bipolar junction, the base-emitter voltage drop changes with temperature. Most transistors have a –2 mV/°C shift in V_{Be}. This shift should be used to determine the thermal effects on V_{Re}, V_{Rc} and V_{GATE} to ensure sufficient gate drive at low and high temperature.

TEXAS
INSTRUMENTS

4.4 Pass Resistor and Filtering Capacitor

If the TL1451's 2.5-V reference is used to supply the base current for the cascode transistor, no pass resistor is required, however if an external zener is selected, a pass resistor R_Z must be selected to dissipate the power loss in the drop from the input voltage. The voltage across the pass resistor is given by:

$$V_{Rz} = V_{IN} - V_Z$$

The pass resistor current is given by:

$$I_{Rz} = I_Z + I_B$$

where I_B is given by:

$$I_B = \frac{I_{SAT}}{\beta}$$

and I_Z is the current necessary to bias the zener diode to sufficient accuracy, typically 5 mA–10 mA, depending on the zener diode used to produce the reference voltage. Thus, the pass resistor can be sized by the equation:

$$Rz = \frac{V_{RZ}}{I_{RZ}} = \frac{V_{IN} - V_Z}{I_Z + \frac{I_{SAT}}{B}}$$

Whether the base voltage is supplied by an external reference voltage such as a zener diode or from the TL1451's reference, the voltage must be stabilized with a filtering capacitor to prevent noise from interfering with the circuit's operation. The base charge (Q_B) required to turn on the cascode transistor is given by:

$$Q_B = I_B \times T_{ON} = \frac{I_{SAT}}{\beta} \times \frac{V_{OUT}}{V_{IN(min)}} \times f$$

Since the goal is to minimize the voltage ripple on this reference voltage, a maximum ripple voltage needs to be selected. If the TL1451's reference is being used, this should be limited to 0.5% or less since it effects voltage regulation. If an external reference voltage is used, 5% ripple is acceptable. Since the 2.5-V reference is used, limit the ripple to 0.1% or 2.5 mV to prevent it from interfering with the regulation.

$$Cz = \frac{Q_B}{V_{RIP}} = \frac{I_{SAT}}{\beta} \times \frac{\frac{V_{OUT}}{V_{IN(min)}}}{V_{RIP}} \times f = \frac{\frac{8\ mA}{100} \times \frac{5\ V}{10\ V}}{2.5\ mV} \times 100\ kHz = 160\ nF$$

When selecting the next larger capacitor, a minimum of 0.22-µF capacitor is used on the reference pin to prevent the cascode's base current from affecting the regulator's operation. For additional filtering between the cascode and the feedback regulator, a capacitor should be placed in parallel with the low side resistor on the reference voltage divider to the error amplifer. This capacitor has the added benefit of providing a softstart function for the TL1451's output to prevent overshoot during start-up.

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