Adjust The Output Of An Inverting Buck-Boost Regulator Without Level Shifting

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Switching power applications sometimes require external adjustment of the output voltage setpoint; one example is an organic light-emitting diode module in vehicles. A common way to adjust the setpoint is to use a microcontroller to generate a variable voltage through either a digital-to-analog converter or an averaged pulse-width modulation signal.

Implementing such a scheme is straightforward when the dc control voltage, input voltage, output voltage and regulator share the same reference—typically the system ground reference (GND). But things get interesting when trying to adjust the output of an inverting buck-boost regulator, where the output voltage is negative and the regulator GND reference is not the same as the system GND.

Typically, a level-shifting circuit is required to accommodate the different ground references, which adds several extra components to the circuit. However, under certain operating conditions, the level shifter can be eliminated and a very simple and straightforward voltage-adjustment scheme can be applied as we propose here.

In this article, we'll present this scheme, derive the equations that describe its operation and then apply them in an application example. That example will also provide us with the basis for discussing the limitations of this voltage-adjustment method.

But to begin, we'll look at a buck regulator example where regulator and system ground are the same and explain how output voltage is typically adjusted with a very simple circuit. Then, we'll describe how a current mirror is typically applied in the case of an inverting buck-boost regulator to provide the needed level shifting of the control voltage.

Output Voltage Adjustment Of A Regulator

Fig. 1 shows a typical implementation of how to adjust the output voltage of a buck converter using a control voltage (V_{cntl}). For illustrative purposes, assuming that the minimum V_{cntl} is equal to the feedback voltage of the regulator, setting the top feedback resistor (R_{FBT}) and the bottom feedback resistor (R_{FBB}) will obtain the highest preferred output voltage level.
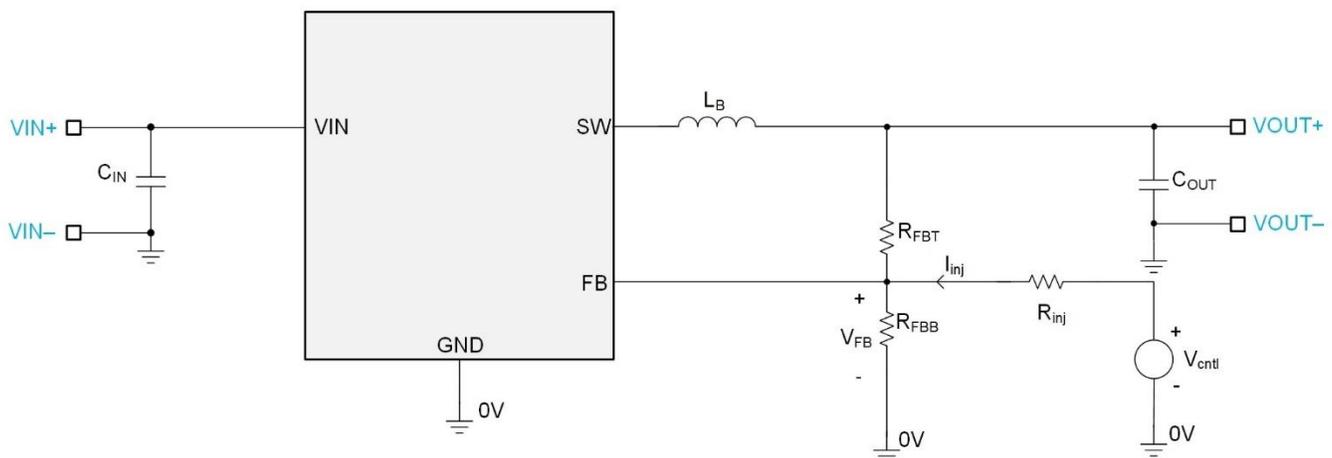

Fig. 1. Typical implementation of an output voltage adjustment for a buck converter.

A control voltage equal to the feedback voltage (V_{FB}) achieves the highest output voltage because there is no current being injected into the feedback node; thus, R_{FBT} and R_{FBB} set the output voltage. No current flows

through the feedback injection resistor (R_{inj}) given the zero voltage potential across it. When increasing V_{cntl} above the feedback voltage, current flows into the feedback node through R_{inj}. The highest V_{cntl} corresponds to the lowest output voltage setpoint.

Equation 1 calculates the current injected (I_{inj}) into the feedback node through the R_{inj}:

$$I_{inj} = \frac{V_{cntl} - V_{ref}}{R_{inj}} \qquad (1)$$

The voltage reduction is the amount of voltage difference between the preferred V_{out} max and V_{out} min setpoints as a result of I_{inj}, as shown by equation 2:

$$V_{OUT_{red}} = I_{inj} \times R_{FBT} \qquad (2)$$

The V_{out} level represents the absolute value of the inverting buck-boost regulator's output voltage, which is a function of the V_{cntl}, as expressed in equation 3:

$$V_{OUT} = V_{ref} \times \left(1 + \frac{R_{FBT}}{R_{FBB}}\right) - V_{OUT_{red}} \qquad (3)$$

where $V_{FB} = V_{ref}$, which is the internal reference voltage of the regulator.

Adjusting the output voltage of an inverting buck-boost regulator with a ground-referenced V_{cntl} often entails the use of a level-shifting scheme to translate the ground-referenced dc voltage to a dc voltage that is referenced to the negative output voltage, i.e., a regulator (device) GND. Fig. 2 illustrates a typical application of such a scheme using a simple current-mirror circuit.
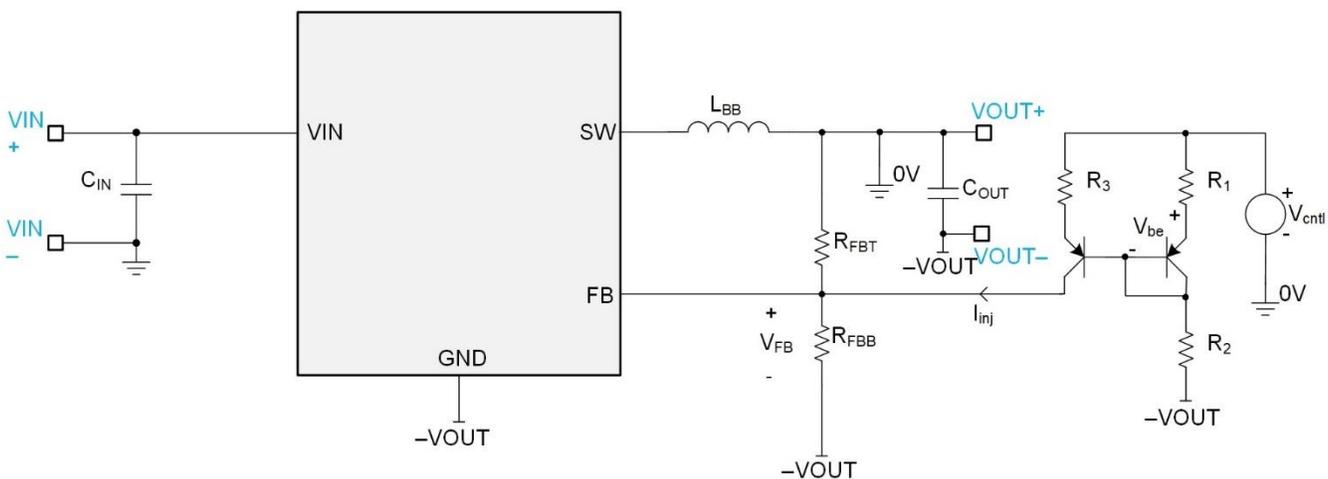

Fig. 2. Adjusting the output voltage of an inverting buck-boost regulator using a current mirror (Note: R1 = R3).

As Fig. 2 shows, implementing a current mirror involves using matched-pair bipolar junction transistors along with a few additional resistors. Equation 4 calculates I_{inj}, which is then applied to equations 2 and 3 in the same manner as described above to determine the adjusted output voltage:

$$I_{inj} = \frac{V_{cntl} - V_{be}}{R_1 + R_2} \qquad (4)$$

However, there is an alternative that doesn't require the additional components of the current mirror. Fig. 3 shows a very simple scheme using a V_{cntl} referenced to system GND (0 V). This method uses only a single injection resistor that connects directly to the feedback node, just as for the buck regulator. Here, current is again injected into the feedback node; however, a different set of equations govern the performance.

Besides reducing the number of parts, this injection-resistor method has an additional advantage: the output is able to scale below the regulator's reference to negative voltage levels slightly below 0 V.
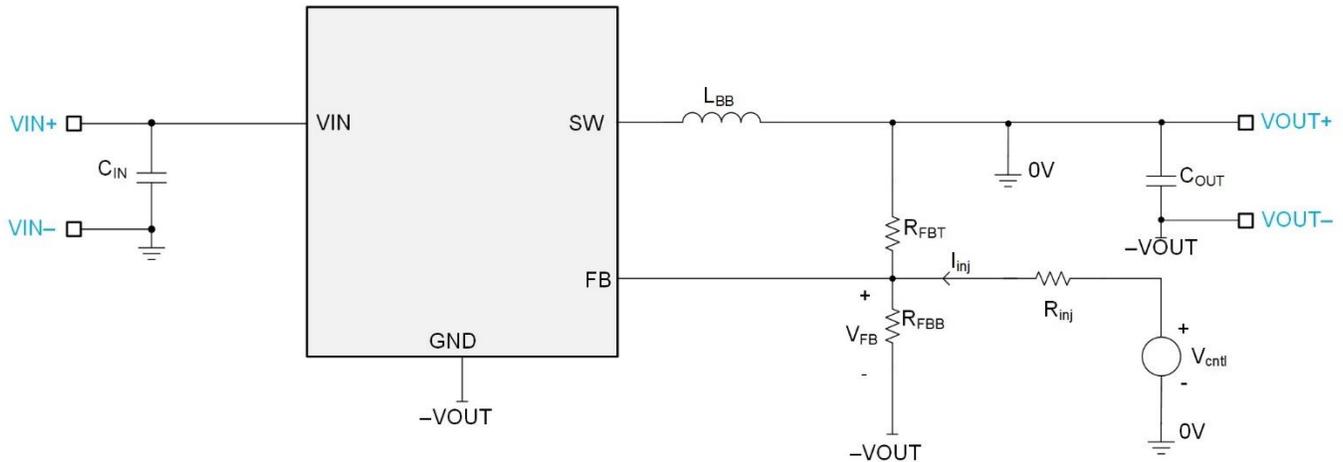

Fig. 3. Inverting buck-boost regulator Vout adjustment with a simple injection resistor.

Deriving Equations For V_out Adjustment With Injection Resistor

Let's calculate the output voltage adjustment for this simple method.

Looking at Fig. 3, you can see that when $V_{cntl} > V_{FB}$, I_{inj} is flowing into the feedback node. Equation 5 shows the current flowing through R_{FBB}:

$$I_{R_{FBB}} = I_{R_{FBT}} + I_{inj} \qquad (5)$$

Equation 6 expresses V_{out} as

$$V_{out} = V_{ref} + \left(I_{R_{FBT}} \times R_{FBT}\right) \qquad (6)$$

Rearranging equation 5 yields equation 7:

$$I_{R_{FBT}} = I_{R_{FBB}} - I_{inj} \qquad (7)$$

Substituting equation 7 into equation 6 yields the absolute value of the output voltage setpoint shown in equation 8, where I_{RFBB} equals V_{ref} divided by R_{FBB} and V_{out} is an absolute value:

$$V_{out} = V_{ref} + \left(\frac{V_{ref}}{R_{FBB}} - I_{inj}\right) \times R_{FBT} \qquad (8)$$

The current I_{inj} through R_{inj} is dependent upon the voltage across it, as shown in Equation 9:

$$I_{inj} = \frac{V_{out} - V_{ref} + V_{cntl}}{R_{inj}} \qquad (9)$$

Substituting I_{inj} from equation 9 into equation 8 and simplifying yields equation 10:

$$V_{out} = \left\{ \left[1 + \frac{R_{inj}}{R_{FBB} \times \left(1 + \frac{R_{inj}}{R_{FBT}} \right)} \right] \times V_{ref} \right\} - \left[\frac{V_{cntl}}{\left(1 + \frac{R_{inj}}{R_{FBT}} \right)} \right] \qquad (10)$$

Application Example

Fig. 4 shows a schematic of an inverting buck-boost regulator with an operating input voltage range of 9 V to 18 V, and an adjustable output voltage of −7.5 V to −12 V capable of sourcing 5 A of current to the load. The V_{cntl} used to adjust the output will be 0 V to 5 V. Table 1 shows the application example parameters.
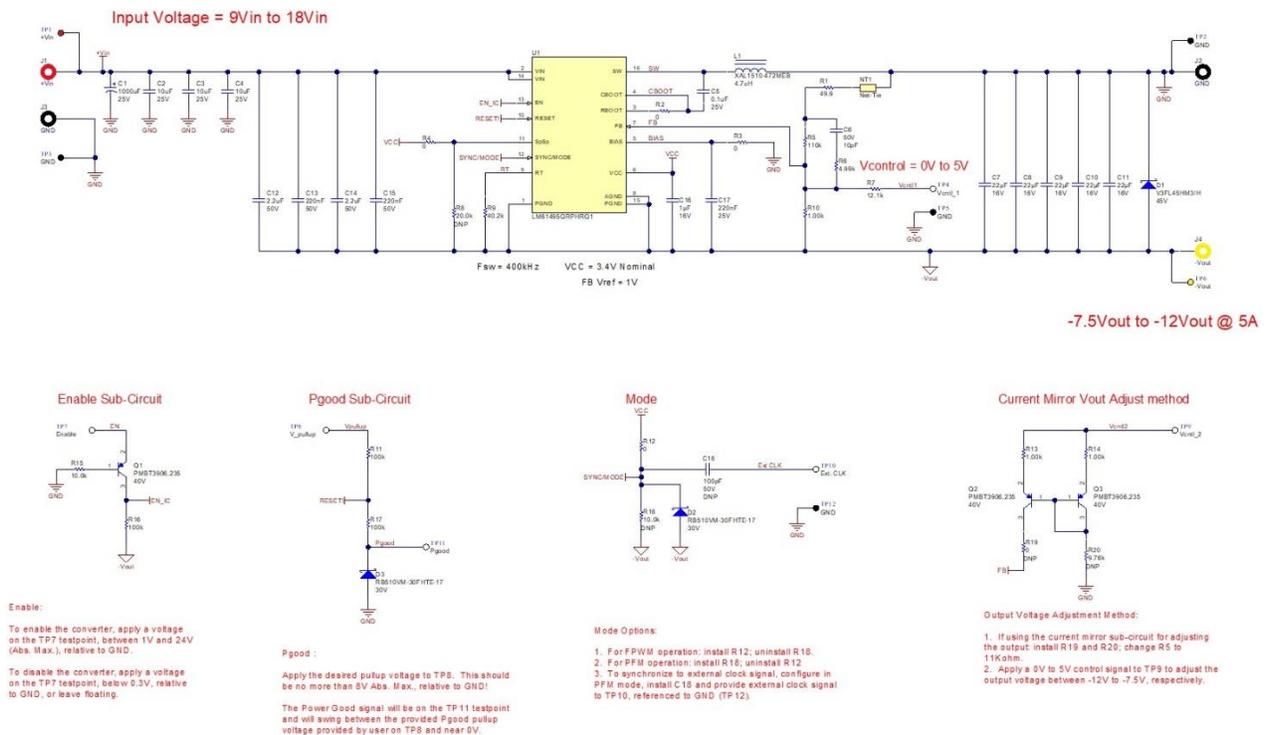

Fig. 4. Inverting buck-boost regulator schematic implementing the I_{inj} V_{out} control using the R_{inj} or optional current-mirror method.

Table 1. Application example parameters.

Parameter	Value	Units
Input voltage range	9 to 18	V
Output voltage range	−7.5 to −12	V
Output current	5	A

V_{cntl} range	0 to 5	V
Switching frequency	400	kHz
V_{ref}	1	V

The following steps show how to select the values in Fig. 4 for the feedback circuit components, using absolute values for the voltages.

In order to determine the correct values for R_{FBB}, R_{FBT} and R_{inj}, first set R_{FBB} to 1 kΩ as a starting point, and then, through algebraic manipulation, solve for the two remaining variables, R_{FBT} and R_{inj}.

Using equation 10, subtract V_{outmin} from V_{outmax}, as shown in equations 11 and 12:

$$V_{out_{max}} - V_{out_{min}} = \left[\left[\left(1 + \frac{R_{inj}}{R_{FBB} \times \left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right) \times V_{ref}\right] - \frac{V_{cntl_{min}}}{\left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right] - \left[\left[\left(1 + \frac{R_{inj}}{R_{FBB} \times \left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right) \times V_{ref}\right] - \frac{V_{cntl_{max}}}{\left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right]$$

$$(11)$$

Equation 11 simplifies to

$$V_{out_{max}} - V_{out_{min}} = \frac{\left(V_{cntl_{max}} - V_{cntl_{min}}\right)}{\left(1 + \frac{R_{inj}}{R_{FBT}}\right)} \qquad (12)$$

Solving equation 12 for R_{inj} yields equation 13:

$$R_{inj} = \left(\frac{V_{cntl_{max}} - V_{cntl_{min}}}{V_{out_{max}} - V_{out_{min}}} - 1\right) \times R_{FBT} \qquad (13)$$

Using equation 10 once again and expressing it in terms of equation 13 for R_{inj} yields equation 14:

$$V_{out_{max}} = \left[1 + \frac{\left(\frac{V_{cntl_{max}} - V_{cntl_{min}}}{V_{out_{max}} - V_{out_{min}}} - 1\right) \times R_{FBT}}{R_{FBB} \times \left[1 + \frac{\left(\frac{V_{cntl_{max}} - V_{cntl_{min}}}{V_{out_{max}} - V_{out_{min}}} - 1\right) \times R_{FBT}}{R_{FBT}}\right]} \times V_{ref}\right] - \left[\frac{V_{cntl_{min}}}{\left[1 + \frac{\left(\frac{V_{cntl_{max}} - V_{cntl_{min}}}{V_{out_{max}} - V_{out_{min}}} - 1\right) \times R_{FBT}}{R_{FBT}}\right]}\right]$$

$$(14)$$

Solving equation 14 for R_{FBT} yields equation 15:

$$R_{FBT} = \left[\frac{\left(V_{out_{max}} \times V_{cntl_{max}} - V_{ref} \times V_{cntl_{max}}\right)}{\left(V_{out_{min}} + V_{cntl_{max}} - V_{out_{max}}\right)}\right] \times \left[\frac{R_{FBB}}{V_{ref}}\right] \qquad (15)$$

Evaluating equation 15 yields an R_{FBT} value of 110 kΩ.

To solve for R_{inj}, once again using equation 10 and expressing it in terms of $V_{out_{max}}$ with its corresponding $V_{cntl_{min}}$ expression, yields equation 16:

$$V_{out_{max}} = \left[\left(1 + \frac{R_{inj}}{R_{FBB} \times \left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right) \times V_{ref}\right] - \left[\frac{V_{cntl_{min}}}{\left(1 + \frac{R_{inj}}{R_{FBT}}\right)}\right] \quad (16)$$

Solving equation 16 for R_{inj} yields equation 17:

$$R_{inj} = \frac{R_{FBT} \times \left(V_{out_{max}} - V_{ref} - V_{cntl_{min}}\right)}{V_{ref} \times \left(1 + \frac{R_{FBT}}{R_{FBB}} - \frac{V_{out_{max}}}{V_{ref}}\right)} \qquad (17)$$

Evaluating equation 17 yields R_{inj} = 12.22 kΩ.

R_{FBB}, R_{FBT} and R_{inj} are now set, providing an output voltage level of –12 V when V_{cntl} equals 0 V and –7.5 V when V_{cntl} equals 5 V.

Limitations

The red line in Fig. 5 shows the actual adjustable output voltage range (absolute) for a varying V_{cntl} from 0 V to 10 V using the values suggested in the previous application example.

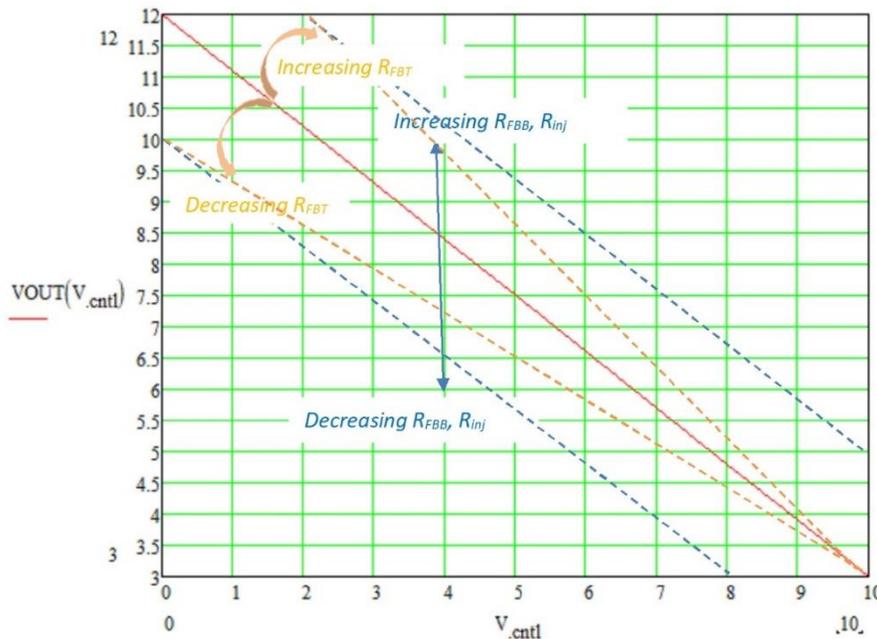*Fig. 5. Visualization of the output voltage range for an inverting buck-boost regulator as a function of V_{cntl} swept from 0 V to 10 V (R_{FBB} = 1 kΩ, R_{FBT} = 110 kΩ and R_{inj} = 12.22 kΩ).*

Fig. 5 includes conceptual curves that describe how V_{out} is affected by increasing or decreasing R_{FBT} and R_{inj}. Note how it is possible to adjust the slope of V_{out} for a given V_{cntl} using different values of R_{inj} and R_{FBT}. If there is a limit on the maximum value of R_{FBT}, the only option is to increase the dynamic range of V_{cntl}.

As a general rule, the dynamic range of the adjustable output voltage is approximately equal to the dynamic range of V_{cntl}. If the maximum value of R_{FBT} or V_{cntl} is limited for a given desired dynamic voltage range, then we recommend employing a level-shifted current injection scheme, as depicted in Fig. 2.

Summary

The typical method for adjusting the output voltage of an inverting buck-boost regulator uses complex level-shifting schemes that require additional components. The simple, injection-resistor method described in this article adjusts the output voltage using a single resistor, without the need for additional components. Calculating values for R_{FBT}, R_{FBB} and R_{inj} is not so trivial, however.

In this article, we provided a logical approach and guidance on how to mathematically set up and reduce the equations for solving the circuit, and selecting component values to meet a given specification. We also discussed limitations of the injection-resistor method and provided further guidance on how to attain wider output voltage adjustment ranges.

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About The Authors

Hrag Kasparian, who joined Texas Instruments over 10 years ago, currently serves as a power applications engineer, designing custom dc-dc switch-mode power supplies. Previously, he worked on development of battery packs, chargers, and electric vehicle (EV) battery management systems at a startup company in Silicon Valley. Hrag graduated from San Jose State University with a bachelor of science in electrical engineering.

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