Design Calculations for Buck-Boost Converters

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ABSTRACT

This application note gives the equations to calculate the power stage of a non-inverting buck-boost converter built with an IC with integrated switches and operating in continuous conduction mode. See the references at the end of this document if more detail is needed.

For a design example without description, see appendix A.

Contents

Figures

1 Basic Configuration of a Buck Boost Converter

Figure 1, shows the basic configuration of a buck-boost converter where the switches are integrated in the IC. Many of the Advanced Low Power buck-boost converters (TPS63xxx) have all four switches integrated in the IC. This reduces solution size and eases the difficultly of the design.

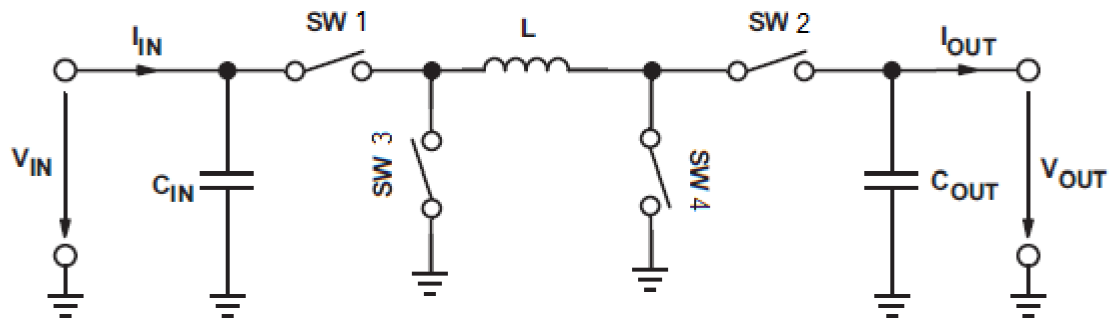

Figure 1. Buck Boost Converter Schematic

1.1 Necessary Parameters of the Power Stage

The following four parameters are needed to calculate the power stage:

1. Input voltage range: Vinmin and Vinmax
2. Nominal output voltage: Vout
3. Maximum output current: Iout
4. Integrated circuit used to build the buck-boost converter. This is necessary because some parameters for the calculations must be derived from the data sheet.

If these parameters are known, the power stage can be calculated.

2 Calculating the Duty Cycle

The first step after selecting the operating parameters of the converter is to calculate the minimum duty cycle for buck mode and maximum duty cycle for boost mode. These duty cycles are important because at these duty cycles the converter is operating at the extremes of its operating range. The duty cycle is always positive and less than 1.

$$Dbuck = \frac{Vout \times \eta}{Vinmax} \quad (1)$$

$$Dboost = 1 - \frac{Vinmin \times \eta}{Vout} \quad (2)$$

Where:

Vinmax = maximum input voltage
Vinmin = minimum input voltage
Vout = desired output voltage
Dbuck = minimum duty cycle for buck mode
Dboost = maximum duty cycle for boost mode
η = estimated efficiency at calculated Vin, Vout, and Iout

3 Inductor Selection

Data sheets often give a range of recommended inductor values. If this is the case, choose an inductor from this range. The higher the inductor value, the higher is the possible maximum output current because of the reduced ripple current.

Normally, the lower the inductor value, the smaller is the solution size. Note that the inductor must always have a higher current rating than the largest value of current given from Equations 5 and 8; this is because the peak current increases with decreasing inductance.

For device datasheets, where no inductor range is given, an inductor that satisfies both buck and boost mode conditions must be chosen. Follow both sections 3.1 and 3.2 to find the right inductance. Select the largest value of inductance calculated from either equations 3 and 4.

3.1 Buck Mode

For buck mode the following equation is a good estimate for the right inductance:

$$L > \frac{Vout \times (Vinmax - Vout)}{K_{ind} \times Fsw \times Vinmax \times Iout} \tag{3}$$

Where:
Vinmax = maximum input voltage
Vout = desired output voltage
Iout = desired maximum output current
Fsw = switching frequency of the converter
Kind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

A good estimation for the inductor ripple current is 20% to 40% of the output current, or 0.2 < Kind < 0.4.

3.2 Boost Mode

For boost mode the following equation is a good estimate for the right inductance:

$$L > \frac{Vinmin^2 \times (Vout - Vinmin)}{Fsw \times K_{ind} \times Iout \times Vout^2} \tag{4}$$

Where:
Vinmin = minimum input voltage
Vout = desired output voltage

Iout = desired maximum output current
Fsw = switching frequency of the converter
Kind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

A good estimation for the inductor ripple current is 20% to 40% of the output current, or 0.2 < Kind < 0.4.

4 Calculating Maximum Switch Current

To calculate the maximum switch current the duty cycle must be derived as done in section 2 of this application note. There are two operating cases to consider for these calculations: buck and boost mode. Derive the maximum switch current for both cases. Use the greater of the two switch currents for remainder of this application note.

4.1 Buck Mode

In buck mode, the maximum switch current is when the input voltage is at its maximum. Using equations 5 and 6, the maximum switch current can be calculated.

$$Iswmax = \frac{\Delta Imax}{2} + Iout \tag{5}$$

$$\Delta Imax = \frac{(Vinmax - Vout) \times Dbuck}{Fsw \times L} \tag{6}$$

Where:
Vinmax = maximum input voltage
Vout = desired output voltage
Iout = desired output current
ΔImax = maximum ripple current through the inductor
Iswmax = maximum switch current
Dbuck = minimum duty cycle for buck mode
Fsw = switching frequency of the converter
L = selected inductor value

To obtain the switching frequency, refer to the datasheet for the given converter.

Before continuing, verify that the converter can deliver the maximum current using equation 7. Imaxout must be greater than Iout.

$$Imaxout = Ilim - \frac{\Delta Imax}{2} \tag{7}$$

Where:
Imaxout = maximum deliverable current through inductor by the converter
Ilim = switch current limit, specified in converter datasheet
ΔImax = Ripple current through the inductor calculated in equation 6.

4.2 Boost Mode

In boost mode, the maximum switch current is when the input voltage is at its minimum. Using equations 8 and 9, the maximum switch current can be calculated.

$$Iswmax = \frac{\Delta Imax}{2} + \frac{Iout}{1 - Dboost} \quad (8)$$

$$\Delta Imax = \frac{Vinmin \times Dboost}{Fsw \times L} \quad (9)$$

Where:
Vinmin = minimum input voltage
Vout = desired output voltage
Iout = desired output current
ΔImax = maximum ripple current through the inductor
Iswmax = maximum switch current
Dboost = maximum duty cycle for boost mode
Fsw= switching frequency of the converter
L = selected inductor value

To obtain the switching frequency, refer to the datasheet for the given converter.

Before continuing, verify that the converter can deliver the maximum current using equation 10. Imaxout must be greater than Ioutmax. Ioutmax is specified as the maximum output current required be the application.

$$Imaxout = \left(Ilim - \frac{\Delta Imax}{2}\right) \times (1 - Dboost) \quad (10)$$

Where:
Imaxout = maximum deliverable current through inductor by the converter
Dboost = maximum duty cycle for boost mode
Ilim = switch current limit, specified in converter datasheet
ΔImax = Ripple current through the inductor calculated in equation 9.

5 Output Voltage Setting

Most converters set the output voltage with a resistive divider network. This is integrated if the converter is a fixed output voltage converter. In this case, the external voltage divider described in this section is not used.

With the given feedback voltage, V_{FB}, and feedback bias current, I_{FB}, the voltage divider can be calculated.

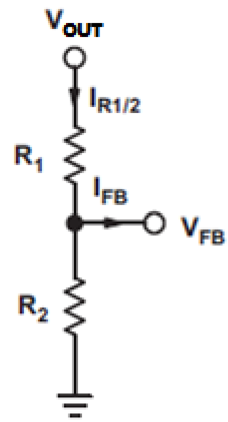

Figure 2. Feedback Circuit

The current through the resistive divider must be at least 100 times the size of the feedback bias current. SLYT469 is also available for a detailed discussion on resistive feedback divider design.

$$I_{R1/2} \geq 100 \times I_{FB} \tag{11}$$

Where:
$I_{R1/2}$ = current through the resistive divider to GND
I_{FB} = feedback bias current from data sheet

This adds less than 1% inaccuracy to the voltage measurement. For the calculation of the feedback divider, the current into the feedback pin can be neglected. The disadvantage of using smaller resistor values than computed from equations 12 and 13 is a higher power loss in the resistive divider and thus lower efficiency at light loads, but the accuracy does increase. Again, for a more detailed discussion on this subject matter see the SLYT469.

Neglecting the current into the FB pin, the resistors are calculated as followed:

$$R2 = \frac{Vfb}{I_{\frac{R1}{2}}} \tag{12}$$

$$R1 = R2 \times (\frac{Vout}{Vfb} - 1) \tag{13}$$

Where:
R_1,R_2 = resistive divider values, see Figure 2.
V_{fb} = feedback voltage from the datasheet
$I_{R1/2}$ = current through the resistive divider to GND, calculated in Equation 11
V_{OUT} = desired output voltage

6 Input Capacitor Selection

The minimum value for the input capacitor is normally given in the datasheet. This minimum value is necessary to stabilize the input voltage due to the peak current requirement of a switching power supply. The best practice is to use low-equivalent series resistance (ESR) ceramic capacitors. The dielectric material must be X5R or better. Otherwise, the capacitor loses much of its capacitance due to dc bias or temperature.

The value can be increased if the input voltage is noisy.

7 Output Capacitor Selection

The best practice is to use low-ESR capacitors to minimize the ripple on the output voltage. Ceramic capacitors are a good choice if the dielectric material is X5R or better.

If the converter has external compensation, any capacitor value above the recommended minimum in the datasheet can be used, but the compensation has to be adjusted for the used output capacitance.

With internally compensated converters, the recommended inductor and capacitor values must be used, or the recommendations in the datasheet for adjusting the output capacitors to the application must be followed. This usually involves keeping the same ratio of L × C as the recommended values.

With external compensation, a solution that satisfies both buck and boost mode must be chosen. Follow both sections 7.1 and 7.2 to develop minimum output capacitance for both buck and boost mode operations. Select output capacitance that is larger than both minimum required output capacitance for buck and boost mode operation. Always account for DC bias capacitance drop and derate the capacitance of the output capacitors for the design calculations.

7.1 Buck Mode

For buck mode, equations 14 and 16 are used to calculate the minimum output capacitor value for a desired output voltage ripple. For the minimum output capacitance use the maximum value from equation 14 and 16.

$$Coutmin1 = \frac{K_{ind} \times Iout}{8 \times Fsw \times Vout_{ripple}} \qquad (14)$$

Where:
Coutmin1 = minimum output capacitance required
Fsw = switching frequency of the converter
$Vout_{ripple}$ = desired output voltage ripple
Iout = desired maximum output current
Kind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

The ESR of the output capacitor adds some more ripple, which can be calculated with equation 15:

$$\Delta Vout_{esr} = ESR \times K_{ind} \times Iout \quad (15)$$

Where:
$\Delta Vout_{esr}$ = additional output voltage ripple due to capacitors ESR
ESR = equivalent series resistance of the used output capacitor

Often the selection of the output capacitor is not driven by the steady-state ripple, but by the output transient response. The output voltage deviation is caused by the time it takes the inductor to catch up with the increased or reduced output current needs.

The following formula can be used to calculate the necessary output capacitance for a desired maximum overshoot caused by the removal of the load current.

$$Coutmin2 = \frac{(K_{ind} \times Iout)^2 \times L}{2 \times Vout \times \Delta Vout} \quad (16)$$

Where:
Coutmin2 = minimum output capacitance required for a desired overshoot
Iout = desired maximum output current
Kind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current
Vout = desired output voltage
ΔVout = desired output voltage change due to the overshoot

7.2 Boost Mode

With external compensation, the following equations can be used to adjust the output capacitor values for a desired output voltage ripple:

$$Coutmin = \frac{Iout \times Dboost}{Fsw \times \Delta Vout} \quad (17)$$

Where:
Coutmin = minimum output capacitance
I_{OUT} = maximum output current of the application
Dboost = duty cycle calculated with Equation 7
Fsw = switching frequency of the converter
Δ Vout = desired output voltage ripple

The ESR of the output capacitor adds some more ripple, given with the equation 18. Be sure to account for this Vout ESR ripple.

$$\Delta Vout_{esr} = ESR \times \left(\frac{Iout}{1 - Dboost} + \frac{K_{ind} \times Iout \times Vout}{2 \times Vin}\right) \quad (18)$$

Where:
$\Delta Vout_{esr}$ = additional output voltage ripple due to capacitors ESR
ESR = equivalent series resistance of the used output capacitor
Iout = maximum output current of the application

Dboost = duty cycle calculated with Equation 7
Kind = estimated coefficient that represents the amount of inductor ripple current relative to the

References

1. *Basic Calculation of a Boost Converter's Power Stage* (SLVA372B)
2. *Basic Calculation of a Buck Converter's Power Stage* (SLVA477)

Appendix A. Design Example Using TPS63020

A.1 System Requirements

Vout = 3.3V
Iout = 2A
Vinmin = 2.6V
Vinmax = 5.5V
Efficiency (3.3Vout @ 5.5Vin) = 91%
Efficiency (3.3Vout @ 2.6Vin) = 74%

A.2 Duty Cycle

For buck mode duty cycle use equation 1, Dbuck = 0.546. For boost mode duty cycle use equation 2, Dboost = 0.417.

A.3 Inductor Selection

Buck

Using Equation 3:

- L=0.917uH, (assuming Kind =0.3)

Boost

Using Equation 4:

- L=0.302uH, (assuming Kind =0.3)

Inductor Selected: 1.0 uH

A.4 Maximum Switch Current

Buck

Using Equations 5 through 7:

- Dbuck = 0.546
- Iripmax = 501mA
- Iswmax = 2.25 A
- Imaxout = 3.75 A which is greater than 2 A

Boost

Using Equations 8 through 10:

- Dboost = 0.417
- Irip = 452 mA
- Iswmax = 3.66 A
- Imaxout = 2.20 A which is greater than 2 A

A.5 Output Voltage Setting

Using equation 11 and assuming I_{FB} = 0.01µA, $I_{R1/2}$ minimum is found to be 1µA. By assuming 3µA for $I_{R1/2}$, 167kΩ is calculated from equation 12 for R2. 169kΩ is chosen for R2. Equation 13 then yields 946kΩ for R1 which, 953kΩ is chosen for R1. The typical output voltage with these values of resistors is 3.32V.

A.6 Input Capacitor Selection

Two 10uF, 6.3V, X5R ceramic capacitors are chosen for the design.

A.7 Output Capacitor Selection

Using equations 14, 16, and 17, the minimum capacitance required is calculated by taking the maximum of these values. Equations 14, 16, and 17 yield 1.04 uF, 1.09 uF, and 11.6 uF. The maximum was the result from equation 17, 11.6 uF. Two 10 uF, 6.3V, X5R, +/- 20% ceramic capacitors, (MuRata, GRM188R60J106ME84), were chosen for the output capacitance. This capacitor is commonly chosen in low power DCDC applications by Texas Instruments due to its enhanced DC-bias performance. By using the manufacture's provided information, the combined derated value of the two output capacitors is 12.9 uF which is sufficient for the minimum output capacitance calculated in equation 17. The use a non-enhanced capacitor with the same specs as the one chosen for this design would probably require a third output capacitor.

IMPORTANT NOTICE

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