Basic Calculation of a Buck Converter's Power Stage

Brigitte Hauke   *Low Power DC/DC Applications*

ABSTRACT

This application report gives the formulas to calculate the power stage of a buck converter built with an integrated circuit having a integrated switch and operating in continuous conduction mode. It is not intended to give details on the functionality of a buck converter or how to compensate a converter. For additional information, see the references at the end of this document.

Appendix A contains the formulas without description.

1 Basic Configuration of a Buck Converter

Figure 1 shows the basic configuration of a buck converter where the switch is integrated in the selected integrated circuit (IC). Some converters have the diode replaced by a second switch integrated into the converter (synchronous converters). If this is the case, all equations in this document apply besides the power dissipation equation of the diode.
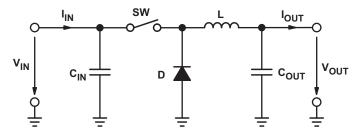

Figure 1. Buck Converter Power Stage

1.1 Necessary Parameters of the Power Stage

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

1. Input voltage range: $V_{IN(min)}$ and $V_{IN(max)}$
2. Nominal output voltage: V_{OUT}
3. Maximum output current: $I_{OUT(max)}$
4. Integrated circuit used to build the buck 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 Calculate the Maximum Switch Current

The first step to calculate the switch current is to determine the duty cycle, D, for the maximum input voltage. The maximum input voltage is used because this leads to the maximum switch current.

$$\text{Maximum Duty Cycle: D} = \frac{V_{OUT}}{V_{IN(max)} \times \eta} \tag{1}$$

$V_{IN(max)}$ = maximum input voltage
V_{OUT} = output voltage

η = efficiency of the converter, e.g., estimated 90%

The efficiency is added to the duty cycle calculation, because the converter also has to deliver the energy dissipated. This calculation gives a more realistic duty cycle than just the formula without the efficiency factor.

Use either an estimated factor, e.g., 90% (which is not unrealistic for a buck converter worst-case efficiency), or see the *Typical Characteristics* section of the data sheet of the selected converter.

The next step in calculating the maximum switch current is to determine the inductor ripple current. In the converter's data sheet; normally, a specific inductor or a range of inductors are named for use with the IC. So, use the recommended inductor value to calculate the ripple current, an inductor value in the middle of the recommended range, or if none is given in the data sheet, the one calculated in the *Inductor Selection* section of this application report.

$$\text{Inductor Ripple Current: } \Delta I_L = \frac{\left(V_{IN(max)} - V_{OUT}\right) \times D}{f_S \times L}$$

(2)

$V_{IN(max)}$ = maximum input voltage
V_{OUT} = desired output voltage
D = duty cycle calculated in Equation 1
f_S = minimum switching frequency of the converter
L = selected inductor value

It now has to be determined if the selected IC can deliver the maximum output current.

$$\text{Maximum output current of the selected IC: } I_{MAXOUT} = I_{LIM(min)} - \frac{\Delta I_L}{2}$$

(3)

$I_{LIM(min)}$ = minimum value of the current limit of the integrated switch (given in the data sheet)
ΔI_L = inductor ripple current calculated in Equation 2

If the calculated value for the maximum output current of the selected IC, I_{MAXOUT}, is below the system's required maximum output current, the switching frequency has to be increased to reduce the ripple current or another IC with a higher switch current limit has to be used.

Only if the calculated value for I_{MAXOUT} is just a little smaller than the needed one, it is possible to use the selected IC with an inductor with higher inductance if it is still in the recommended range. A higher inductance reduces the ripple current and therefore increases the maximum output current with the selected IC.

If the calculated value is above the maximum output current of the application, the maximum switch current in the system is calculated:

$$\text{Application specific maximum switch current: } I_{SW(max)} = \frac{\Delta I_L}{2} + I_{OUT(max)}$$

(4)

ΔI_L = inductor ripple current calculated in Equation 2
$I_{OUT(max)}$ = maximum output current necessary in the application

This is the peak current, the inductor, the integrated switch(es), and the external diode have to withstand.

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 maximum output current because of the reduced ripple current.

In general, the lower the inductor value, the smaller is the solution size. Note that the inductor must always have a higher current rating than the maximum current given in Equation 4; this is because the current increases with decreasing inductance.

For parts where no inductor range is given, the following equation is a good estimation for the right inductor:

$$L = \frac{V_{OUT} \times \left(V_{IN} - V_{OUT}\right)}{\Delta I_L \times f_S \times V_{IN}}$$

(5)

V_{IN} = typical input voltage
V_{OUT} = desired output voltage
f_S = minimum switching frequency of the converter
ΔI_L = estimated inductor ripple current, see the following:

The inductor ripple current cannot be calculated with Equation 1 because the inductor is not known. A good estimation for the inductor ripple current is 20% to 40% of the output current.

$$\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)}$$

(6)

ΔI_L = estimated inductor ripple current
$I_{OUT(max)}$ = maximum output current necessary in the application

4   Rectifier Diode Selection

To reduce losses, use Schottky diodes. The forward current rating needed is equal to the maximum output current:

$$I_F = I_{OUT(max)} \times (1 - D)$$

(7)

I_F = average forward current of the rectifier diode
$I_{OUT(max)}$ = maximum output current necessary in the application

Schottky diodes have a much higher peak current rating than average rating. Therefore the higher peak current in the system is not a problem.

The other parameter that has to be checked is the power dissipation of the diode. It has to handle:

$$P_D = I_F \times V_F$$

(8)

I_F = average forward current of the receiver diode
V_F = forward voltage of the rectified diode
D = duty cycle calculated in Equation 1

5   Output Voltage Setting

Almost all converters set the output voltage with a resistive divider network (which is integrated if they are fixed output voltage converters).

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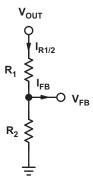

Figure 2. Resistive Divider for Setting the Output Voltage

The current through the resistive divider needs to be at least 100 times as big as the feedback bias current:

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

(9)

$I_{R1/2}$ = 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 and for the calculation of the feedback divider, the current into the feedback pin can be neglected. The current also can be a lot higher. The only disadvantage of smaller resistor values is a higher power loss in the resistive divider, but the accuracy is increased a little.

With the preceding assumption, the resistors are calculated as follows:

$$R_2 = \frac{V_{FB}}{I_{R1/2}}$$

(10)

$$R_1 = R_2 \times \left(\frac{V_{OUT}}{V_{FB}} - 1 \right)$$

(11)

R_1, R_2 = resistive divider, see Figure 2.
V_{FB} = feedback voltage from the data sheet
$I_{R1/2}$ = current through the resistive divider to GND, calculated in Equation 9
V_{OUT} = desired output voltage

6 Input Capacitor Selection

The minimum value for the input capacitor is normally given in the data sheet. 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 data sheet 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 data sheet for adjusting the output capacitors to the application in the data sheet must be followed for the ratio of L × C.

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

$$C_{OUT(min)} = \frac{\Delta I_L}{8 \times f_S \times \Delta V_{OUT}}$$

(12)

$C_{OUT(min)}$ = minimum output capacitance
ΔI_L = estimated inductor ripple current
f_S = minimum switching frequency of the converter
ΔV_{OUT} = desired output voltage ripple

The ESR of the output capacitor adds some more ripple, given with the equation:

$$\Delta V_{OUT(ESR)} = ESR \times \Delta I_L$$

(13)

$\Delta V_{OUT(ESR)}$ = additional output voltage ripple due to capacitors ESR
ESR = equivalent series resistance of the used output capacitor
ΔI_L = inductor ripple current from Equation 2 or Equation 6

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:

$$C_{OUT(min),OS} = \frac{\Delta I_{OUT}^2 \times L}{2 \times V_{OUT} \times V_{OS}}$$

(14)

$C_{OUT(min),OS}$ = minimum output capacitance for a desired overshoot
ΔI_{OUT} = maximum output current change in the application
V_{OUT} = desired output voltage
V_{OS} = desired output voltage change due to the overshoot

8   References

1. *Understanding Buck Power Stages in Switchmode Power Supplies* (SLVA057)
2. *Examples of Applications with the Pulse Width Modulator TL5001* (SLVAE05)
3. *Understanding Output Voltage Limitations of DC/DC Buck Converters* (SLYT293)
4. *Designing Ultrafast Loop Response With Type-III Compensation for Current Mode Step-Down Converters* (SLVA352)
5. Robert W. Erickson: *Fundamentals of Power Electronics*, Kluwer Academic Publishers, 1997
6. Mohan/Underland/Robbins: *Power Electronics*, John Wiley & Sons Inc., Second Edition, 1995
7. George M. Harayda, Akira Omi, and Axel Yamamoto: *Improve Your Designs with Large Capacitance Value Multi-Layer Ceramic Chip* (MLCC) Capacitors, Panasonic
8. Jeffrey Cain, Ph.D.: *Comparison of Multilayer Ceramic and Tantalum Capacitors*, AVX Corporation

Formulas to Calculate the Power State of a Buck Converter

Maximum Duty Cycle: $D = \dfrac{V_{OUT} \times \eta}{V_{IN(max)}}$

(15)

$V_{IN(max)}$ = maximum input voltage
V_{OUT} = output voltage
η = efficiency of the converter, e.g., estimated 85%

Inductor Ripple Current: $\Delta I_L = \dfrac{\left(V_{IN(max)} - V_{OUT}\right) \times D}{f_S \times L}$

(16)

$V_{IN(max)}$ = maximum input voltage
V_{OUT} = desired output voltage
D = duty cycle calculated in Equation 15
f_S = minimum switching frequency of the converter
L = selected inductor value

Maximum output current of the selected IC: $I_{MAXOUT} = I_{LIM(min)} - \dfrac{\Delta I_L}{2}$

(17)

$I_{LIM(min)}$ = minimum value of the current limit of the integrated switch (given in the data sheet)
ΔI_L = inductor ripple current calculated in Equation 16

Application specific maximum switch current: $I_{SW(max)} = \dfrac{\Delta I_L}{2} + I_{OUT(max)}$

(18)

ΔI_L = inductor ripple current calculated in Equation 16
$I_{OUT(max)}$ = maximum output current necessary in the application

Inductor Calculation: $L = \dfrac{V_{OUT} \times (V_{IN} - V_{OUT})}{\Delta I_L \times f_S \times V_{IN}}$ (if no value is recommended in the data sheet)

(19)

V_{IN} = typical input voltage
V_{OUT} = desired output voltage
f_S = minimum switching frequency of the converter
ΔI_L = estimated inductor ripple current, see next paragraph

Inductor Ripple Current Estimation: $\Delta I_L = (0.2 \text{ to } 0.4) \times I_{OUT(max)}$

(20)

ΔI_L = estimated inductor ripple current
$I_{OUT(max)}$ = maximum output current necessary in the application

Average Forward Current of Rectifier Diode: $I_F = I_{OUT(max)} \times (1 - D)$

(21)

$I_{OUT(max)}$ = maximum output current necessary in the application
D = duty cycle calculated in Equation 1

Power Dissipation in Rectifier Diode: $P_D = I_F \times V_F$

(22)

I_F = average forward current of the rectifier diode
V_F = forward voltage of the rectifier diode
D = duty cycle calculated in Equation 1

Current through Resistive Divider Network for Output Voltage Setting: $I_{R1/2} \geq 100 \times I_{FB}$

(23)

I_{FB} = feedback bias current from data sheet

Value of Resistor Between FB Pin and GND: $R_2 = \dfrac{V_{FB}}{I_{R1/2}}$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (24)

Value of Resistor Between FB Pin and V_{OUT}: $R_1 = R_2 \times \left(\dfrac{V_{OUT}}{V_{FB}} - 1 \right)$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (25)

V_{FB} = feedback voltage from the data sheet
$I_{R1/2}$ = current through the resistive divider to GND, calculated in Equation 23
V_{OUT} = desired output voltage

Minimum Output Capacitance, if not given in Data Sheet: $C_{OUT(min)} = \dfrac{\Delta I_L}{8 \times f_S \times \Delta V_{OUT}}$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (26)

ΔI_L = estimated inductor ripple current
f_S = minimum switching frequency of the converter
ΔV_{OUT} = desired output voltage ripple

Additional Output Voltage Ripple due to ESR: $\Delta V_{OUT(ESR)} = ESR \times \Delta I_L$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (27)

ESR = equivalent series resistance of the used output capacitor
$I_{OUT(max)}$ = maximum output current of the application
ΔI_L = inductor ripple current from Equation 16 or Equation 20

Output Voltage Overshoot due to Load Transient: $C_{OUT(min),OS} = \dfrac{\Delta I_{OUT}^2 \times L}{2 \times V_{OUT} \times V_{OS}}$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (28)

ΔI_{OUT} = maximum output current change in the application
V_{out} = desired output voltage
V_{OS} = desired output voltage change due to the overshoot

Revision History

Changes from A Revision (August 2012) to B Revision **Page**

• Changed equation 1 and supporting text in *Calculate the Maximum Switch Current* section.................................. 1

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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