

Switching Regulator IC Series

Inductor Calculation for Buck Converter IC

No.12027ECY01

This application note covers the steps required in choosing the inductor and to calculate the value used in buck regulator IC circuits.

• Buck (Step-Down) Converter

Switching regulators are used in a variety of applications to provide stable and efficient power conversion. A buck converter is a specific type of switching regulator that steps down the input voltage to a lower level output.

Fig. 1 shows a typical buck converter circuit when switching element Q1 is ON. When N-ch MOSFET Q1 is ON, current flowing from input V_{IN} to coil L charges the output capacitor C_o and supplies output current I_o . In this scenario, the current flowing through coil L produces a magnetic field and electric energy is converted to magnetic energy to be stored.

Fig. 2 illustrates the same circuit when switching element Q1 is in an OFF state. When Q1 is OFF, free-wheeling diode D1 is activated, and the energy stored in coil L is released.

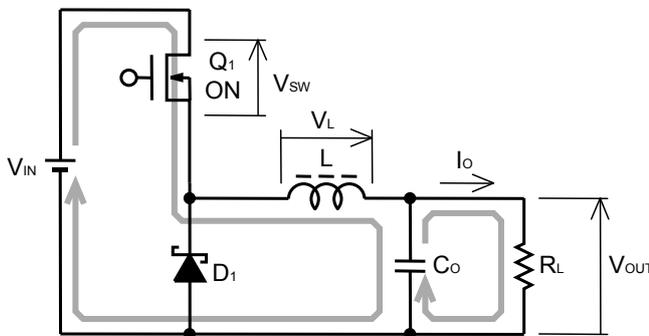


Fig. 1: Basic Buck Converter Circuit Switching Element ON

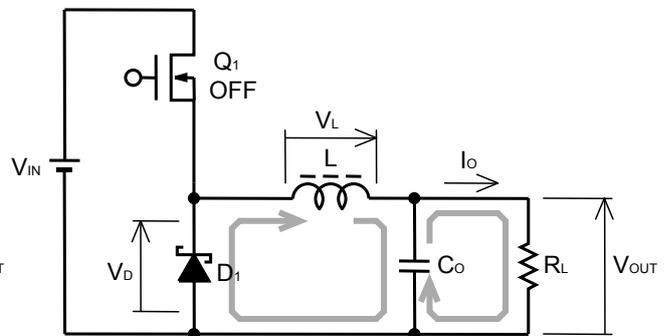


Fig. 2: Basic Buck Converter Circuit Switching Element OFF

• Inductor Current Waveform

Fig. 3 shows the inductor's current waveform. I_{OUT} is the average inductor current value. When switching element Q1 is ON, current flow is shown during ON period t_{ON} of Q1, and voltage $V_{L(ON)}$ of coil L can be calculated by the following equation:

$$V_{L(ON)} = -(V_{IN} - V_{SW} - V_{OUT}) \quad (1)$$

V_{IN} : Input Voltage (V)
 V_{SW} : Q1 ON-state Voltage Drop (V)
 V_{OUT} : Output Voltage (V)

The relation between current I_L and voltage V_L of coil L, which has self-inductance, can be calculated using the equation below:

$$V_L = -L \frac{dI_L}{dt} \quad (2)$$

From equation (2), it is clear that by applying additional voltage to the inductor, the reverse-current direction increases by slope V/L .

Current flowing through the coil during t_{ON} can be calculated using equation (1), (2), and by the following method; I_{LT} represents current right before switching element Q1 turns ON, I_{LP} represents current right before switching element Q1 turns OFF.

$$I_{LP} - I_{LT} = -\frac{(V_{SW} - V_{IN} + V_{OUT}) \times t_{ON}}{L} \quad (3)$$

The next step is to determine current flow in coil L when the switching element is OFF.

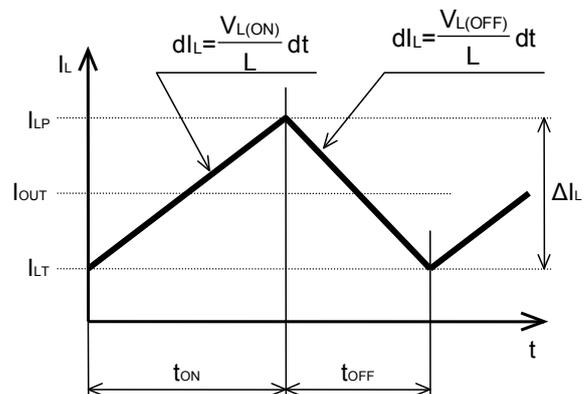


Fig. 3: Inductor Current Waveform

From Fig. 2, the coil voltage when Q1 in OFF- state is $V_{L(OFF)}$, can be calculated using the following method:

$$V_{L(OFF)} = V_D + V_{OUT} \quad (4)$$

V_D : Forward Voltage Drop across D1 (V)
 V_{OUT} : Output Voltage (V)

Using equations (2) and (4), the current flowing through coil L when Q1 is OFF is as follows:

$$I_{LP} - I_{LT} = \frac{(V_D + V_{OUT}) \times t_{OFF}}{L} \quad (5)$$

Current flow in the coil L is almost the same as the output current; consequently,

$$I_{LP} + I_{LT} = 2 \times I_{OUT} \quad (6)$$

From equations (3) and (6), I_{LP} during Q1 ON-state is

$$I_{LP} = I_{OUT} + \frac{(V_{IN} - V_{SW} - V_{OUT}) \times t_{ON}}{2 \times L} \quad (7)$$

Using equations (5) and (6), I_{LP} can be calculated during the period when the switching element is OFF:

$$I_{LP} = I_{OUT} + \frac{(V_D + V_{OUT}) \times t_{OFF}}{2 \times L} \quad (8)$$

- On-Duty Calculation

On-duty D is the ratio of time the switching element is ON t_{ON} versus the switching oscillatory cycle T_{SW} :

$$D = \frac{t_{ON}}{T_{SW}} = \frac{t_{ON}}{t_{ON} + t_{OFF}} = t_{ON} \times f_{SW} = 1 - (t_{OFF} \times f_{SW}) \quad (9)$$

Using (7), (8), and (9), the duty can be calculated using the expression below:

$$D = \frac{V_D + V_{OUT}}{V_{IN} - V_{SW} + V_D} \quad (10)$$

By ignoring the voltage drop V_{SW} of the switching element and voltage drop of the diode in equation (10), it is clear that on-duty is fixed by the ratio of output voltage over input voltage:

$$D \cong \frac{V_{OUT}}{V_{IN}} \quad (11)$$

- Maximum Coil Current Value

Use equations (9) and (10) to determine t_{ON} :

$$t_{ON} = \frac{D}{f_{SW}} = \frac{V_D + V_{OUT}}{(V_{IN} - V_{SW} + V_D) \times f_{SW}} \quad (12)$$

The equation below determines the maximum value of I_{LP} by substituting (12) into (7):

$$I_{LP} = I_{OUT} + \frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times 2 \times L \times f_{SW}} \quad (13)$$

Equation (14) is used to determine the minimum value I_{LT} by substituting (13) into (6):

$$I_{LT} = I_{OUT} - \frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times 2 \times L \times f_{SW}} \quad (14)$$

Current-difference between max. and min. ($I_{LP} - I_{LT}$) is as follows:

$$(I_{LP} - I_{LT}) = \frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times L \times f_{SW}} \quad (15)$$

Equations (13) and (15) show that large inductance L and high switching frequency will reduce maximum current (I_{LP}) and current difference between max. and min. ($I_{LP} - I_{LT}$).

- Inductance L Value Calculation

Define the ratio of current-difference flowing in coil L ($I_{LP} - I_{LT}$) versus output current I_{OUT} as current ripple-ratio "r".

$$r = \frac{\Delta I_L}{I_{OUT}} = \frac{I_{LP} - I_{LT}}{I_{OUT}} \quad (16)$$

Substitute (15) into (16):

$$r = \frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times f_{SW} \times L \times I_{OUT}} \quad (17)$$

Then, solve (17) for L to calculate the inductance value:

$$L = \frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times f_{SW} \times r \times I_{OUT}} \quad (H) \quad (18-1)$$

When the output voltage is high, the calculation can be simplified.

$$L = \frac{(V_{IN} - V_{OUT}) \times V_{OUT}}{V_{IN} \times f_{SW} \times r \times I_{OUT}} \quad (H) \quad (18-2)$$

The inductor value can be increased to reduce the ripple-ratio; however, this will typically result in an inductor size that is physically too big for practical use. Consequently, "r" is usually set between 0.2 and 0.5 for buck converters.

- Maximum Current Flow through the Coil

Maximum current flow through the coil can be calculated using the following equation:

$$I_{Lpeak} = I_{OUT} + \frac{r \times I_{OUT}}{2} \quad (A) \quad \text{or} \quad = I_{OUT} + \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{2 \times V_{IN} \times f_{SW} \times L} \quad (A) \quad (19)$$

Current flowing through the coil is a combination of output current and ripple-current. When an abnormality occurs (ex. output short) in a transient load condition and there will be a power surge due to the absence of soft-start feature, and it is possible that the actual current flow through the inductor will exceed the maximum calculated current. Under transient conditions, coil current may increase up to the IC's switching current limit. Therefore, the safest approach is to select an inductor with a saturation current rating that exceeds the switching current limit, and not the maximum coil current.

- Effective RMS current flowing through the coil

Effective current value of triangular wave can be calculated by the following method.

$$I_{Lrms} = \sqrt{\frac{I_{LP}^2 + I_{LT}^2 + I_{LP} \times I_{LT}}{3}} \quad (20)$$

By substituting equations (13) and (14) into (20), we arrive at the following:

$$I_{Lrms} = \sqrt{I_{OUT}^2 + \frac{1}{12} \times \left(\frac{(V_{IN} - V_{SW} - V_{OUT}) \times (V_D + V_{OUT})}{(V_{IN} - V_{SW} + V_D) \times L \times f_{SW}} \right)^2} \quad (A) \quad (21)$$

• Example for Coil selection:

Determine the operating conditions of the buck converter:

- $V_{IN} = 12V$ Input Voltage
- $V_{OUT} = 3.3V$ Output Voltage
- $I_{OUT} = 2A$ Output Current
- $r = 0.3$ Output Current Ripple Ratio
- $V_{SW} = 0.30$ ON State Voltage Drop of Switching Element Q1
- $V_D = 0.26$ * Forward Voltage Drop of Free Wheel Diode
- $f_{sw} = 380$ kHz Switching Frequency

* For synchronized rectifier type power conversion, specify ON-state voltage drop of lower side element Q2 (Fig. 4).

Calculate the inductance value of the coil by substituting the above parameters into equation (18-1) or (18-2).

$$\text{As per equation (18-1), } L = \frac{(12 - 0.30 - 3.3) \times (0.26 + 3.3)}{(12 - 0.30 + 0.26) \times 380000 \times 0.3 \times 2} = 10.663 \text{ } (\mu\text{H})$$

$$\text{As per equation (18-2), } L = \frac{(12 - 3.3) \times 3.3}{12 \times 380000 \times 0.3 \times 2} = 10.493 \text{ } (\mu\text{H})$$

Using equation (19), the maximum current flowing through the coil is as follows:

$$I_{L\text{peak}} = I_{OUT} + \frac{r \times I_{OUT}}{2} = 2 + \frac{0.3 \times 2}{2} = 2.3 \text{ (A)}$$

As per equation (21), the effective current value flowing through the coil is

$$I_{L\text{rms}} = \sqrt{2^2 + \frac{1}{12} \times \left(\frac{(12 - 0.30 - 3.3) \times (0.26 + 3.3)}{(12 - 0.30 + 0.26) \times 10.663 \times 10^{-6} \times 380000} \right)^2} = 2.008 \text{ (A)}$$

Coil selection should be based on the results of the calculations. For this design, 10 μ H is chosen as the closest standard inductance value. If the selected inductor value is different from the calculated result, adjust the current ripple value “r” using equation (17), and substitute the revised value into equation (19) to recalculate the maximum current flowing through the coil.

$$r = \frac{(12 - 0.30 - 3.3) \times (0.26 + 3.3)}{(12 - 0.30 + 0.26) \times 380000 \times 10 \times 10^{-6} \times 2} = 0.329$$

$$I_{L\text{peak}} = 2 + \frac{0.329 \times 2}{2} = 2.33 \text{ (A)}$$

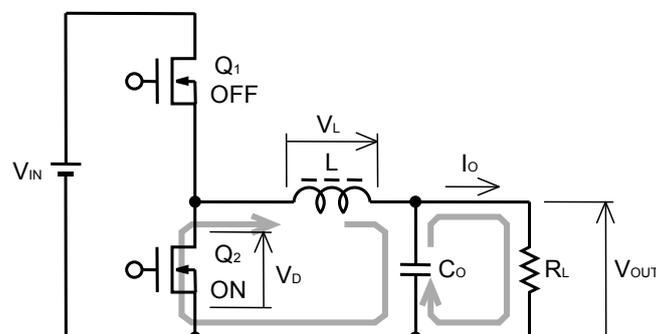


Fig. 4: Basic circuit configuration of a buck converter using synchronous rectification power conversion. In this example, the upper switching element is in OFF-state.

Notes

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