Switching Regulator IC series

Capacitor Calculation for Buck converter IC

This application note explains the calculation of external capacitor value for buck converter IC circuit.

Buck converter

Figure 1 is the basic circuit of buck converter. When switching element Q_1 is ON, current flows from V_{IN} through the coil L and charges the output smoothing capacitor C_O, and the output current I_O is supplied. The current which flows into the coil L at this time induces a magnetic field, and electric energy is transformed into magnetic energy and accumulated for storage.

When switching element Q_1 is OFF, free-wheeling diode D turns ON and energy stored in L is then released to the output side.

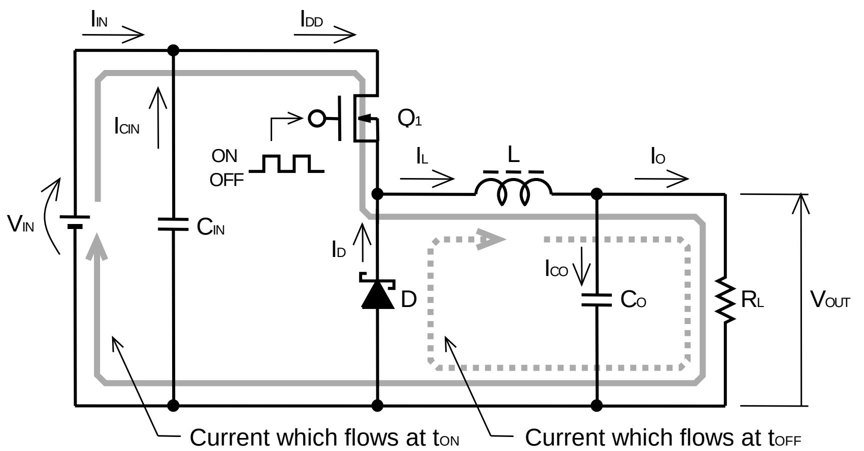


Figure 1. Basic buck converter circuit

Calculation of Input capacitor

Rated voltage of input capacitor must be higher than the maximum input voltage. Also rated ripple-current of the capacitor must be higher than the maximum input ripple-current of the IC.

Although the average value of an input current becomes smaller in proportion to the transformation ratio, momentarily the same current equal to output current flows through the buck converter as shown as I_{DD} in Figure 2.

This will be averaged by the input capacitor, but as it is clearly shown as I_{CIN} of Figure 2, the alternating ripple-current flowing in the input capacitor, is higher than I_{CO} of the output.

Effective value of I_{CIN} can be calculated by following equation:

$$I_{CIN} = \sqrt{\frac{V_{OUT}}{V_{IN(MIN)}}\left\{I_O^2\left(1-\frac{V_{OUT}}{V_{IN(MIN)}}\right)+\frac{1}{12}\Delta I_L^2\right\}} \quad [\mathrm{A_{RMS}}] \qquad (1)$$

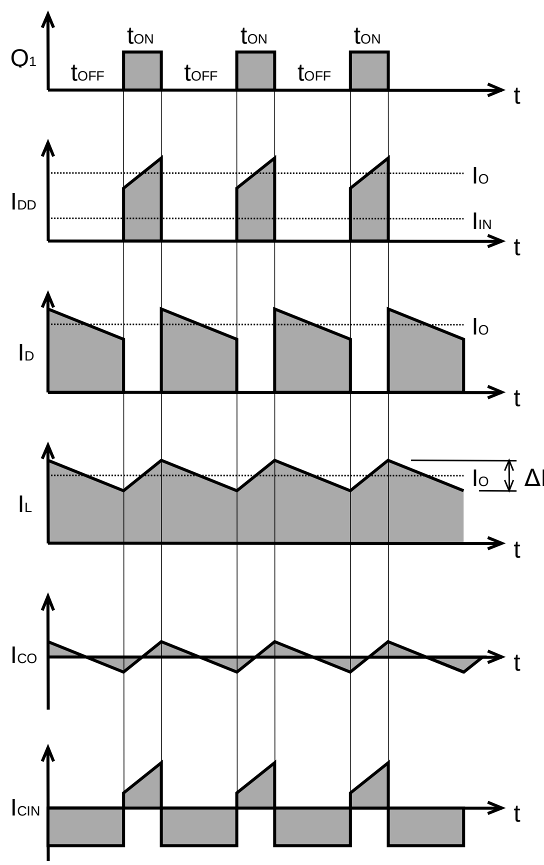


Figure 2. Current waveform of each part

Figure 3 shows the ripple heat generation characteristics of a ceramic capacitor (by Murata Manufacturing Co.). Whether it can be used as input capacitor or not is decided by this graph and the absolute maximum rating of ripple-current.

Be well aware of the temperature and DC bias impressed to the capacitor when using ceramic capacitor.

Change of capacitance value due to temperature can obtain stable temperature characteristic by using high permittivity ceramic capacitor with the characteristics of X5R and X7R.

Capacitance value reduces when DC bias at both sides of ceramic capacitor increases. Figure 4 shows the DC bias characteristics (by Murata Manufacturing Co.).

Example: Characteristic of Ceramic Capacitor (make: Murata Manufacturing Co.)

GRM32ER7YA106KA12 10μF±10%, 35V, X7R

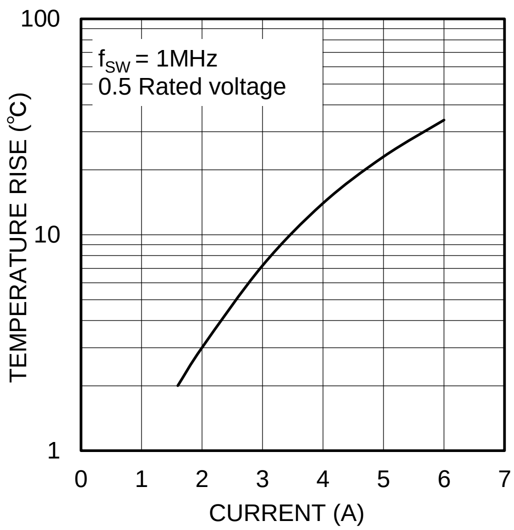


Figure 3. Ripple heat generation characteristic

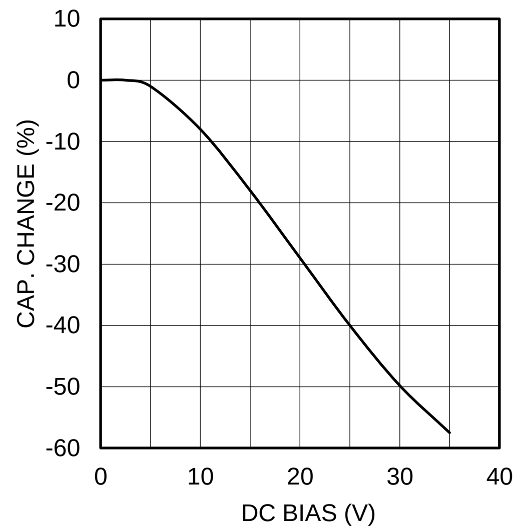


Figure 4. DC bias characteristic

Input ripple voltage of regulator is decided by the value of input capacitance. Input ripple voltage ΔV_{IN} can be calculated by the following equation.

$$\Delta V_{IN} = \frac{\left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times I_{O(MAX)} \times V_{OUT}}{C_{IN} \times f_{SW} \times V_{IN}} + \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times I_{O(MAX)} \times ESR_{MAX} \quad [\mathrm{V_{P-P}}] \qquad (2)$$

V_{IN}: Input voltage [V]

V_{OUT}: Output voltage [V]

$I_{O(MAX)}$: Maximum load current [A]

C_{IN}: Input capacitor [F]

f_{SW}: Switching frequency [Hz]

ESR_{MAX}: Maximum equivalent series resistance ESR [Ω] of input capacitor

Calculation example of input capacitor

For this design example, parameters listed in Table1 will be used. As for the input capacitor, Murata Manufacturing Co. make10µF / 35V ceramic capacitor is considered for reference.

Parameter	Value
Input voltage range V_{IN}	7V to 28V
Output voltage V_{OUT}	3.3V
Input ripple voltage ΔV_{IN}	300mV
Output ripple voltage ΔV_{O}	33mV (1% of output voltage)
Output rating current I_{O}	3A
Inductor ripple current ΔI_{L}	0.9A (30% of output rating current)
Operation frequency f_{SW}	1MHz

Table1. Design parameter

Calculate input ripple current by substituting each parameter to the equation (1).

$$I_{CIN}=\sqrt{\frac{V_{OUT}}{V_{IN(MIN)}}\left\{{I_O}^2\left(1-\frac{V_{OUT}}{V_{IN(MIN)}}\right)+\frac{1}{12}\Delta {I_L}^2\right\}}=\sqrt{\frac{3.3}{7}\left\{3^2\left(1-\frac{3.3}{7}\right)+\frac{1}{12}\times 0.9^2\right\}}=1.508\ [\mathrm{A_{RMS}}] \quad (3)$$

From Figure 3 ripple current capacitance obtains enough margins.

Next, calculate input ripple voltage by substituting each parameter to equation (2). At this point consideration for DC bias characteristic of ceramic capacitor is necessary. In this example, since the maximum voltage impressed to capacitor is 28V, 48% will be reduced from rating capacitance value as from Figure 4. Also, ESR of ceramic capacitor is 2mΩ.

$$\Delta V_{IN}=\frac{\left(1-\frac{V_{OUT}}{V_{IN}}\right)\times I_{O(MAX)}\times V_{OUT}}{C_{IN}\times f_{SW}\times V_{IN}}+\left(1-\frac{V_{OUT}}{V_{IN}}\right)\times I_{O(MAX)}\times ESR_{MAX}\quad [\mathrm{V_{P-P}}]$$

$$=\frac{\left(1-\frac{3.3}{28}\right)\times 3\times 3.3}{(10\times 10^{-6}\times 0.52)\times 1\times 10^{6}\times 28}+\left(1-\frac{3.3}{28}\right)\times(3\times 2\times 10^{-3})=65.3\ [\mathrm{mV_{P-P}}] \quad (4)$$

Ripple voltage of minimum input voltage can be shown as below method.

$$\Delta V_{IN}=\frac{\left(1-\frac{3.3}{7}\right)\times 3\times 3.3}{(10\times 10^{-6}\times 0.96)\times 1\times 10^{6}\times 7}+\left(1-\frac{3.3}{7}\right)\times(3\times 2\times 10^{-3})=81.0\ [\mathrm{mV_{P-P}}] \quad (5)$$

The design requirement for input ripple voltage below 300mV can be confirmed. Maximum voltage at both ends of input capacitor is $V_{IN(MAX)}+\Delta V_{IN}/2$. To obtain more voltage margins, give consideration of using two 4.7µF / 50V capacitors in parallel. Also, be cautious for actual input ripple voltage that may get higher than the calculated value, due to output impedance of the voltage source (preceding circuit) and parasitic component resulting from the PCB layout.

Calculation of output capacitor

Important elements in designing output capacitor are rating voltage, ripple rating current, and ESR (equivalent series resistance). Ripple current and voltage impressed to the capacitor must be less than the maximum rating. ESR is an important element to decide the output ripple voltage with the inductor current.

The effective value of ripple current, the alternating component included in the output current, can be calculated by the following equation as it is a triangular waveform like I_{CO} of Figure 2.

$$\boxed{I_{CO} = \frac{1}{\sqrt{12}} \times \frac{V_{OUT}(V_{IN(MAX)} - V_{OUT})}{L \times f_{SW} \times V_{IN(MAX)}} \quad [\mathrm{A_{RMS}}]} \tag{6}$$

$V_{IN(MAX)}$: Maximum input voltage [V]

V_{OUT}: Output voltage [V]

L : Inductor value [H]

f_{SW}: Switching frequency [Hz]

Output ripple voltage is the composite waveform created by the ripple current of the inductor flowing through the output capacitor depending on electrostatic capacitance, ESR, and ESL. It can be calculated by the following equation.

$$\boxed{\Delta V_{ORPL} = \Delta I_L \left(\frac{1}{8 \times C_O \times f_{SW}} + ESR \right) + ESL \frac{V_{IN(MAX)}}{L} \quad [\mathrm{V_{P\text{-}P}}]} \tag{7}$$

$V_{IN(MAX)}$: Maximum input voltage [V]

ΔI_L: Inductor ripple current [A]

C_O: Output capacitor [F]

L : Inductor value [H]

f_{SW}: Switching frequency [Hz]

ESR: Equivalent series resistor of output capacitor [Ω]

ESL: Equivalent series inductor of output capacitor [H]

When using leaded type aluminum electrolytic capacitor with high ESR and ESL as an output capacitor, notice that ripple by ESR and ESL may get bigger than the ripple by capacitance.

Calculation example of output capacitor

For this design example, parameters listed in Table 1 will be used. As for the input capacitor, Murata Manufacturing Co. make 22µF / 25V ceramic capacitor is considered as reference. Calculate ripple current by substituting each parameter to equation (6). Use 4.7µH value for coil L.

$$I_{CO} = \frac{1}{\sqrt{12}} \times \frac{V_{OUT}(V_{IN(MAX)} - V_{OUT})}{L \times f_{SW} \times V_{IN(MAX)}} = \frac{1}{\sqrt{12}} \times \frac{3.3(28-3.3)}{4.7\times10^{-6}\times1\times10^{6}\times28} = 0.18 \quad [\mathrm{A_{RMS}}] \tag{8}$$

From Figure 5 ripple current capacitance obtains enough margin.

Next, calculate output ripple voltage by substituting each parameter to equation (7). At this point consideration for DC bias characteristic of ceramic capacitor is necessary. In this example, because the voltage impressed to capacitor is 3.3V, 2% will be reduced from rating capacitance value as in Figure 6. Also, ESR of ceramic capacitor is 2mΩ and ESL is 0.4nH.

$$\Delta V_{ORPL} = \Delta I_L \left(\frac{1}{8\times C_O\times f_{SW}} + ESR\right) + ESL\frac{V_{IN(MAX)}}{L}$$

$$= 0.9\left(\frac{1}{8\times(22\times10^{-6}\times0.98)\times1\times10^{6}} + 2\times10^{-3}\right) + 0.4\times10^{-9}\left(\frac{28}{4.7\times10^{-6}}\right) = 9.4 \ [\mathrm{mV_{P\text{-}P}}] \tag{9}$$

Output ripple voltage requirement is 33mV, meaning that the above value satisfies. But, the actual output ripple voltage can be influenced by ESR, ESL elements of capacitor and by parasitic element originated in PCB layout, causing difference from the calculated value.

Example: Characteristic of Ceramic Capacitor (make: Murata Manufacturing Co.)

GRM32ER71E226ME15 22µF±20%, 25V, X7R

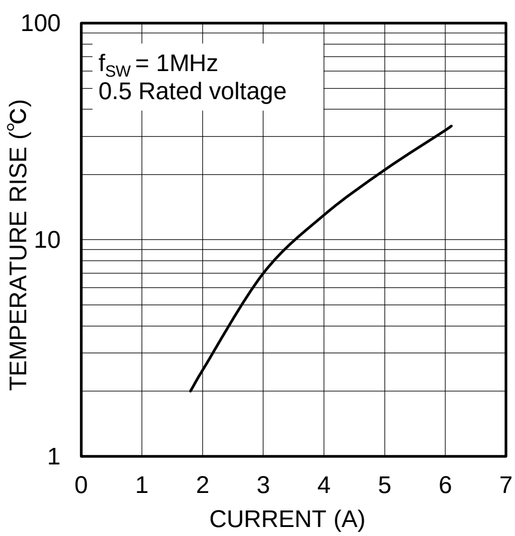


Figure 5. Ripple heat generation characteristic

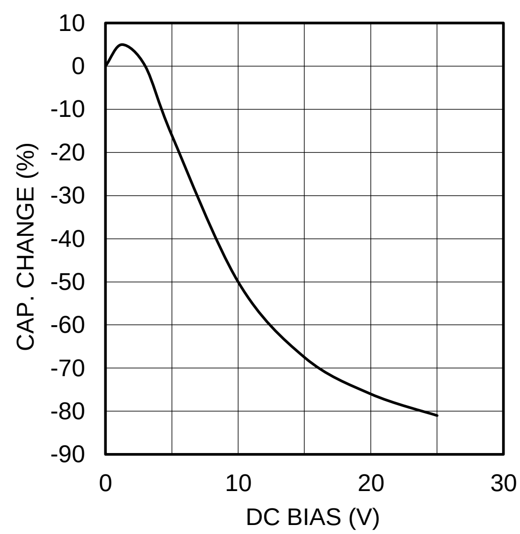


Figure 6. DC bias characteristic

Equation of buck converter

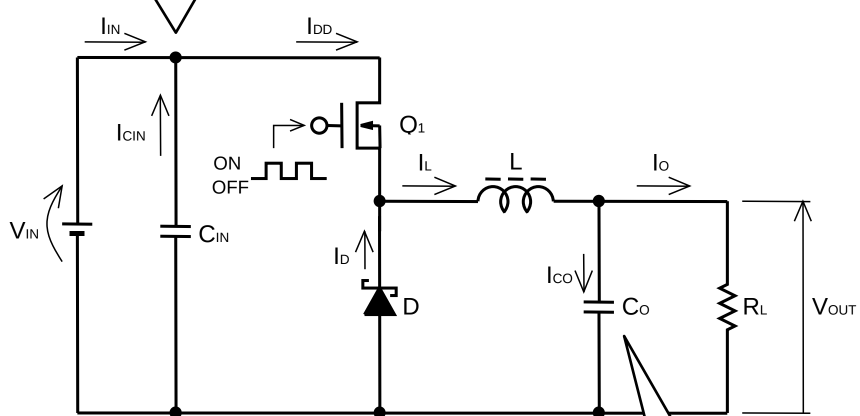
・Effective value of ripple current flowing in input capacitor

$$I_{CIN} = \sqrt{\frac{V_{OUT}}{V_{IN(MIN)}}\left\{ {I_O}^2\left(1 - \frac{V_{OUT}}{V_{IN(MIN)}}\right) + \frac{1}{12}\Delta {I_L}^2 \right\}} \quad [\mathrm{A_{RMS}}]$$

・Input ripple voltage

$$\Delta V_{IN} = \frac{\left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times I_{O(MAX)} \times V_{OUT}}{C_{IN} \times f_{SW} \times V_{IN}} + \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times I_{O(MAX)} \times ESR_{MAX} \quad [\mathrm{V_{P-P}}]$$

V_{IN}: Input voltage [V]
$V_{IN(MIN)}$: Minimum input voltage [V]
V_{OUT}: Output voltage [V]
I_O: Output rating current [A]
ΔI_O: Inductor ripple current [A]
(Usually set between 20% and 50% of I_O)
$I_{O(MAX)}$: Maximum load current [A]
C_{IN}: Input capacitor [F]
f_{SW}: Switching frequency [Hz]
ESR_{MAX}: Maximum equivalent series resistance of Input capacitor [Ω]



Buck converter

・Effective value of ripple current flowing in output capacitor

$$I_{CO} = \frac{1}{\sqrt{12}} \times \frac{V_{OUT}\left(V_{IN(MAX)} - V_{OUT}\right)}{L \times f_{SW} \times V_{IN(MAX)}} \quad [\mathrm{A_{RMS}}]$$

・Output ripple voltage

$$\Delta V_{ORPL} = \Delta I_L \left(\frac{1}{8 \times C_O \times f_{SW}} + ESR\right) + ESL\frac{V_{IN(MAX)}}{L} \quad [\mathrm{V_{P-P}}]$$

$V_{IN(MAX)}$: Maximum input voltage [V]
V_{OUT}: Output voltage [V]
L　L: Inductor value [H]
f_{SW}: Switching frequency [Hz]
ΔI_L: Inductor ripple current [A]
(Usually set between 20% and 50% of I_O)
C_O: Output capacitor [F]
ESR: Equivalent series resistance of output capacitor [Ω]
ESL: Equivalent series inductance of output capacitor [H]

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