Efficiency of Buck Converter

Switching regulators are known as being highly efficient power sources. To further improve their efficiency, it is helpful to understand the basic mechanism of power loss. This application note explains power loss factors and methods for calculating them. It also explains how the relative importance of power loss factors depends on the specifications of the switching power source.

Synchronous rectification type

Figure 1 shows the circuit diagram of a synchronous rectification type DC/DC converter. Figure 2 shows the waveforms of the voltage of a switch node and the current waveform of the inductor. The striped patterns represent the areas where the loss occurs.

The following nine factors are the main causes of power loss:

1. Conduction loss caused by the on-resistance of the MOSFET P_{ON-H}, P_{ON-L}
2. Switching-loss in the MOSFET P_{SW-H}, P_{SW-L}
3. Reverse recovery loss in the body diode P_{DIODE}
4. Output capacitance loss in the MOSFET P_{COSS}
5. Dead time loss P_D
6. Gate charge loss in the MOSFET P_G
7. Operation loss caused by the IC control circuit P_{IC}
8. Conduction loss in the inductor $P_{L(DCR)}$
9. Loss in the capacitor P_{CIN}, P_{COUT}

Conduction loss in the MOSFET

The conduction loss in the MOSFET is calculated in the A and B sections of the waveform in Figure 2. As the high-side MOSFET is ON and the low-side MOSFET is OFF in the A section, the conduction loss of the high-side MOSFET can be estimated from the output current, on-resistance, and on-duty cycle. As the high-side MOSFET is OFF and the low-side MOSFET is ON in the B section, the conduction loss of the low-side MOSFET can be estimated from the output current, on-resistance, and off-duty cycle.
The conduction losses P_{ON-H} and P_{ON-L} are calculated with the following equations.

High-side MOSFET

$$P_{ON-H} = I_{OUT}{}^2 \times R_{ON-H} \times \frac{V_{OUT}}{V_{IN}} \ [W] \qquad (1)$$

Low-side MOSFET

$$P_{ON-L} = I_{OUT}{}^2 \times R_{ON-L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \ [W] \qquad (2)$$

I_{OUT}: Output current $[A]$
R_{ON-H}: High-side MOSFET on-resistance $[\Omega]$
R_{ON-L}: Low-side MOSFET on-resistance $[\Omega]$
V_{IN}: Input voltage $[V]$
V_{OUT}: Output voltage $[V]$

In the equations (1) and (2), the output current is used as the current value. This is the average current of the inductor. As shown in the lower part of Figure 2, greater losses are generated in the actual ramp waveforms. If the current waveform is sharper (peak current is higher), the effective current is obtained by integrating the square of the differential between the peak and bottom values of the current. The loss can then be calculated in more detail.
The conduction losses P_{ON-H} and P_{ON-L} are calculated with the following equations.

High-side MOSFET

$$P_{ON-H} = \left[I_{OUT}{}^2 + \frac{(I_P - I_V)^2}{12}\right] \times R_{ON-H} \times \frac{V_{OUT}}{V_{IN}} \ [W] \qquad (3)$$

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Low-side MOSFET

$$P_{ON-L} = \left[{I_{OUT}}^2 + \frac{(I_P - I_V)^2}{12}\right] \times R_{ON-L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad [W] \qquad (4)$$

$$\Delta I_L = \frac{(V_{IN} - V_{OUT})}{f_{SW} \times L} \times \frac{V_{OUT}}{V_{IN}} \quad [A]$$

$$I_P = I_{OUT} + \frac{\Delta I_L}{2} \quad [A]$$

$$I_P = I_{OUT}$$

I_{OUT}: Output current $[A]$
I_P: Inductor current peak $[A]$
I_V: Inductor current bottom $[A]$
R_{ON-H}: High-side MOSFET on-resistance $[\Omega]$
R_{ON-L}: Low-side MOSFET on-resistance $[\Omega]$
V_{IN}: Input voltage $[V]$
V_{OUT}: Output voltage $[V]$
ΔI_L: Ripple current of inductor $[A]$
f_{SW}: Switching frequency $[Hz]$
L: Inductance value $[H]$

Switching-loss in the MOSFET

The switching-losses are calculated in the C and D sections or in the E and F sections of the waveform in Figure 2. When the high-side and low-side MOSFETs are turned ON and OFF alternately, a loss is generated during the transition of the on-switching. Since the equation for calculating the area of the two triangles is similar to the equation for calculating the power losses during the rising and falling transitions, this calculation can be approximated using a simple geometric equation.
The switching-loss P_{SW-H} is calculated with the following equation.

High-side MOSFET

$$P_{SW-H} = \frac{1}{2} \times V_{IN} \times I_{OUT} \times (t_{r-H} + t_{f-H}) \times f_{SW} \quad [W] \qquad (5)$$

V_{IN}: Input voltage $[V]$
I_{OUT}: Output current $[A]$
t_{r-H}: High-side MOSFET rise time $[sec]$
t_{f-H}: High-side MOSFET rise time $[sec]$
f_{SW}: Switching frequency $[Hz]$

When the low-side MOSFET is turned ON by the gate voltage while the body diode is energized and then the FET is turned OFF by the gate voltage, the load current continues to flow in the same direction through the body diode. Therefore, the drain voltage becomes equal to the forward direction voltage and remains low. Then, the resulting switching-loss P_{SWL} is very small, as described in the following equation.

Low-side MOSFET

$$P_{SW-L} = \frac{1}{2} \times V_D \times I_{OUT} \times (t_{r-L} + t_{f-L}) \times f_{SW} \quad [W] \qquad (6)$$

V_D: Forward direction voltage of
low-side MOSFET body diode $[V]$
I_{OUT}: Output current $[A]$
t_{r-L}: Low-side MOSFET rise time $[sec]$
t_{f-L}: Low-side MOSFET rise time $[sec]$
f_{SW}: Switching frequency $[Hz]$

Reverse recovery loss in the body diode

When the high-side MOSFET is turned ON, the transition of the body diode of the low-side MOSFET from the forward direction to the reverse bias state causes a diode recovery, which in turn generates a reverse recovery loss in the body diode. This loss is determined by the reverse recovery time of the diode t_{RR}. From the reverse recovery properties of the diode, the loss is calculated with the following equation.

$$P_{DIODE} = \frac{1}{2} \times V_{IN} \times I_{RR} \times t_{RR} \times f_{SW} \quad [W] \qquad (7)$$

V_{IN}: Input voltage $[V]$
I_{RR}: Peak value of
body diode reverse recovery current $[A]$
t_{RR}: Body diode reverse recovery time
f_{SW}: Switching frequency $[Hz]$

Output capacitance loss in the MOSFET

In each switching cycle, the loss is generated because the output capacitances of the high-side MOSFETs C_{OSS} are charged. This loss is calculated with the following equation. The charge/discharge loss of C_{OSS} in the low-side MOSFET is usually ignored because the charge of C_{OSS} is already discharged by the inductor current when low-side MOSFET turns on, resulting in ZVS (Zero Voltage Switching).

$$P_{COSS} = \frac{1}{2} \times C_{OSS-H} \times {V_{IN}}^2 \times f_{SW} \quad [W] \tag{8}$$

$$C_{OSS-H} = C_{DS-H} + C_{GD-H} \quad [F]$$

C_{OSS-H}: High-side MOSFET output capacitance $[F]$
C_{DS-H}: High-side MOSFET drain-source capacitance $[F]$
C_{GD-H}: High-side MOSFET gate-drain capacitance $[F]$
V_{IN}: Input voltage $[V]$
f_{SW}: Switching frequency $[Hz]$

Dead time loss

When the high-side and low-side MOSFETs are turned ON simultaneously, a short circuit occurs between the VIN and ground, generating a very large current spike. A period of dead time is provided for turning OFF both of the MOSFETs to prevent such current spikes from occurring, while the inductor current continues to flow. During the dead time, this inductor current flows to the body diode of the low-side MOSFET. The dead time loss P_D is calculated in the G and H sections of the waveform in Figure 2 with the following equation.

$$P_D = V_D \times I_{OUT} \times \left(t_{Dr} + t_{Df}\right) \times f_{SW} \quad [W] \tag{9}$$

V_D: Forward direction voltage of low-side MOSFET body diode $[V]$
I_{OUT}: Output current $[A]$
t_{Dr}: Dead time for rising $[sec]$
t_{Df}: Dead time for falling $[sec]$
f_{SW}: Switching frequency $[Hz]$

Gate charge loss

The Gate charge loss is the power loss caused by charging the gate of the MOSFET. The gate charge loss depends on the gate charges (or gate capacitances) of the high-side and low-side MOSFETs. It is calculated with the following equations.

$$P_G = \left(Q_{g-H} + Q_{g-L}\right) \times V_{gs} \times f_{SW} \quad [W] \tag{10}$$

or

$$P_G = (C_{GS-H} + C_{GS-L}) \times {V_{gs}}^2 \times f_{SW} \quad [W] \tag{11}$$

Q_{g-H}: Gate charge of high-side MOSFET $[C]$
Q_{g-L}: Gate charge of low-side MOSFET $[C]$
C_{GS-H}: Gate capacitance of high-side MOSFET $[F]$
C_{GS-L}: Gate capacitance of low-side MOSFET $[F]$
V_{gs}: Gate drive voltage $[V]$
f_{SW}: Switching frequency $[Hz]$

Operation loss caused by the IC

The consumption power used by the IC control circuit P_{IC} is calculated with the following equation.

$$P_{IC} = V_{IN} \times I_{CC} \quad [W] \tag{12}$$

V_{IN}: Input voltage $[V]$
I_{CC}: IC current consumption $[A]$

Conduction loss in the inductor

There are two types of the power loss in the inductor: the conduction loss caused by the resistance and the core loss determined by the magnetic properties. Since the calculation of the core loss is too complex, it is not described in this article. The conduction loss is generated by the DC resistance (DCR) of the winding that forms the inductor. The DCR increases as the wire length increases; on the other hand, it decreases as the wire cross-section increases. If this trend is applied to the inductor parts, the DCR increases as the inductance value increases and decreases as the case size increases.
The conduction loss of the inductor can be estimated with the following equation. Since the inductor is always energized, it is not affected by the duty cycle. Since the power loss is proportional to the square of the current, a higher output current results in a greater loss. For this reason, it is important to select the appropriate inductors.

$$P_{L(DCR)} = {I_{OUT}}^2 \times \mathrm{DCR} \quad [W] \tag{13}$$

I_{OUT}: Output current $[A]$
DCR: Inductor direct current resistance $[\Omega]$

Since the output current is used in this equation, the average current of the inductor is used for the calculation. Similar to the above-mentioned calculation for the conduction loss of the MOSFET, the loss can be calculated in more detail by using the ramp waveform for the inductor current calculation.

$$P_{L(DCR)} = \left[I_{OUT}^2 + \frac{(I_P - I_V)^2}{12} \right] \times DCR \ \ [W] \tag{14}$$

I_{OUT}: Output current $[A]$
I_P: Inductor current peak $[A]$
I_V: Inductor current bottom $[A]$
DCR: Inductor direct current resistance $[\Omega]$

Loss in the capacitor

Although several losses are generated in the capacitor—including series resistance, leakage, and dielectric loss—these losses are simplified into a general loss model as equivalent series resistance (ESR). The power loss in the capacitor is calculated by multiplying the ESR by the square of the RMS value of the AC current flowing through the capacitor.

$$P_{CAP(ESR)} = I_{CAP(RMS)}^2 \times ESR \ \ [W] \tag{15}$$

$I_{CAP(RMS)}$: RMS current of capacitor $[A]$
ESR: Equivalent series resistance of capacitor $[\Omega]$

The RMS current in the input capacitor is complex, but it can be estimated with the following equation.

$$I_{CIN(RMS)} = I_{OUT} \times \frac{\sqrt{(V_{IN} - V_{OUT}) \times V_{OUT}}}{V_{IN}} \ \ [A] \tag{16}$$

V_{IN}: Input voltage $[V]$
V_{OUT}: Output voltage $[V]$
I_{OUT}: Output current $[A]$

The RMS current in the output capacitor is equal to the RMS value of the ripple current in the inductor, and calculated with the following equation.

$$I_{COUT(RMS)} = \frac{\Delta I_L}{2\sqrt{3}} \ \ [A] \tag{17}$$

ΔI_L: Ripple current of inductor $[A]$

$$\Delta I_L = \frac{(V_{IN} - V_{OUT})}{f_{SW} \times L} \times \frac{V_{OUT}}{V_{IN}} \ \ [A] \tag{18}$$

V_{IN}: Input voltage $[V]$
V_{OUT}: Output voltage $[V]$
f_{SW}: Switching frequency $[Hz]$
L: Inductance value $[H]$

The losses in the input capacitor P_{CIN} and the output capacitor P_{COUT} are calculated by substituting the RMS current in the equation (15) by those calculated in the equations (16) and (17), respectively.

Total power loss

The power loss of the IC, *P*, is obtained by adding all the losses together.

$$P = P_{ON-H} + P_{ON-L} + P_{SW-H} + P_{SW-L} + P_{DIODE} + P_{COSS} + P_D + P_G + P_{IC} + P_{L(DCR)} + P_{CIN} + P_{COUT} \ \ [W] \tag{19}$$

P_{ON-H}: Conduction loss of high-side MOSFET $[W]$
P_{ON-L}: Conduction loss of low-side MOSFET $[W]$
P_{SW-H}: Switching-loss of high-side MOSFET $[W]$
P_{SW-L}: Switching-loss of low-side MOSFET $[W]$
P_{DIODE}: Reverse recovery loss of body diode $[W]$
P_{COSS}: Output capacitance loss of MOSFET $[W]$
P_D: Dead time loss $[W]$
P_G: Gate charge loss $[W]$
P_{IC}: IC operation loss $[W]$
$P_{L(DCR)}$: Conduction loss of inductor $[W]$
P_{CIN}: Input capacitor loss $[W]$
P_{COUT}: Output capacitor loss $[W]$

Efficiency

Since the total power loss is obtained, the efficiency can be calculated with the following equation.

$$\eta = \frac{V_{OUT} \times I_{OUT}}{V_{OUT} \times I_{OUT} + P} \tag{20}$$

V_{OUT}: Output voltage $[V]$
I_{OUT}: Output current $[A]$
P: Total power loss $[W]$

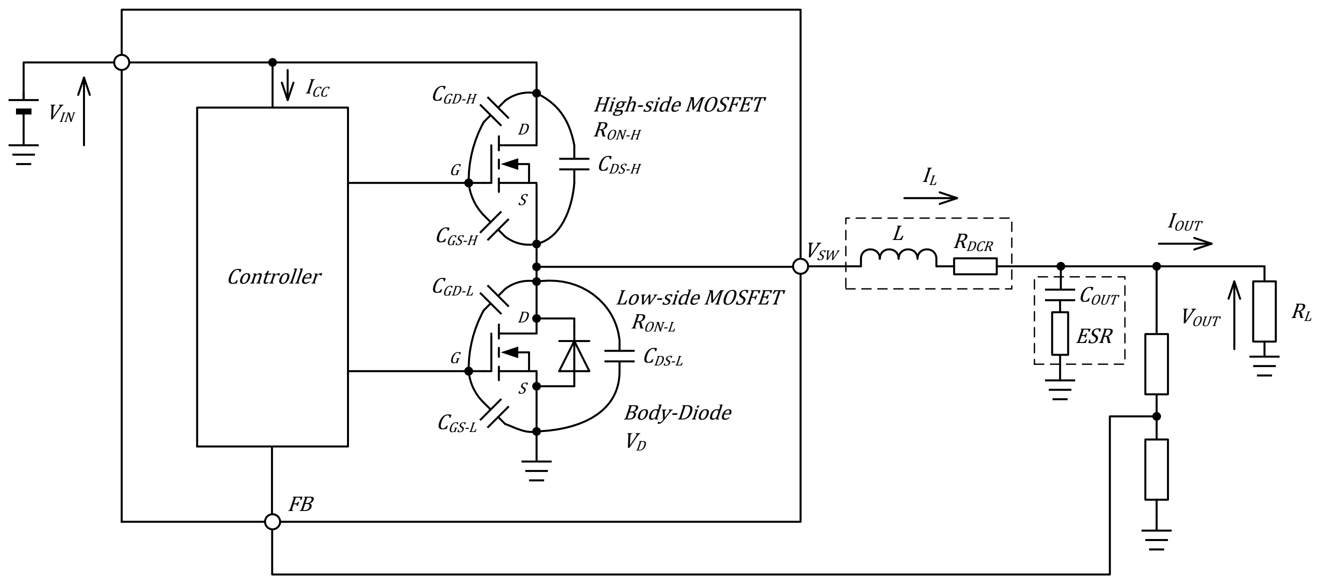


Figure 1. Circuit diagram of the synchronous rectification type DC/DC converter

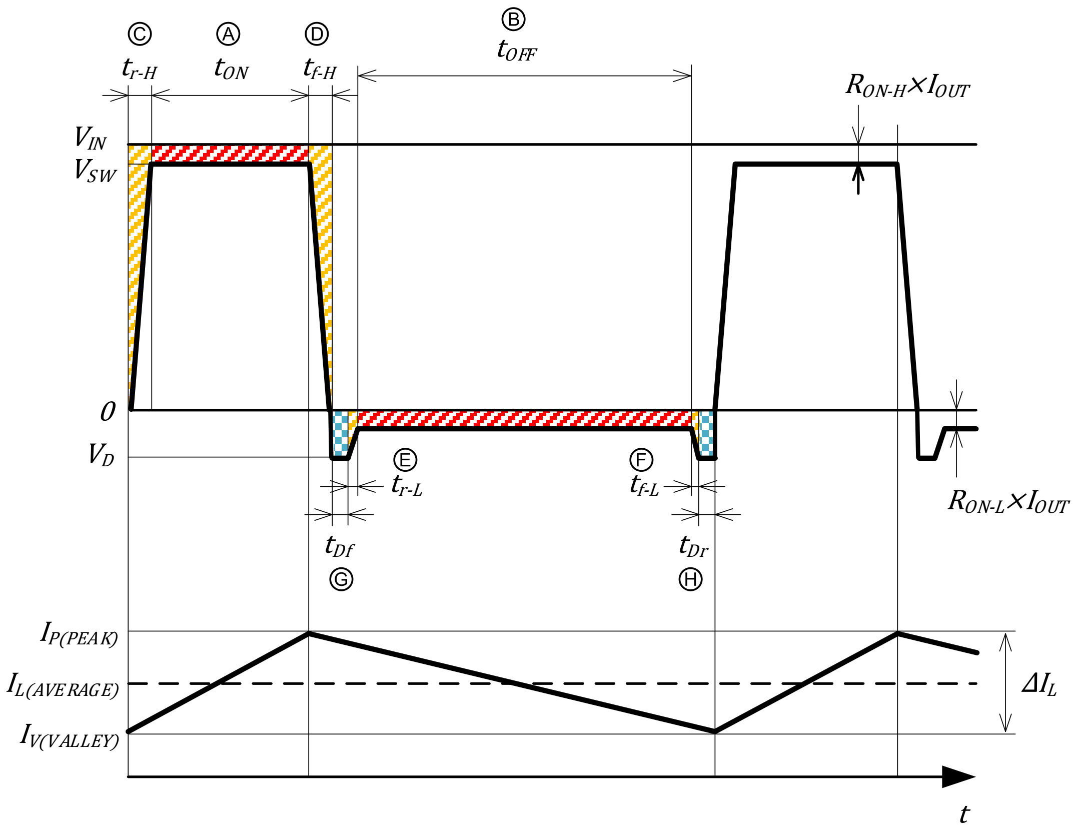


Figure 2. Switching waveform and loss

Calculation example (synchronous rectification type)

Calculation formula	Parameters	Result
1. Conduction loss $P_{ON-H} = \left[{I_{OUT}}^2 + \frac{(I_P - I_V)^2}{12} \right] \times R_{ON-H} \times \frac{V_{OUT}}{V_{IN}}$ $[W]$ $P_{ON-L} = \left[{I_{OUT}}^2 + \frac{(I_P - I_V)^2}{12} \right] \times R_{ON-L} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$ $[W]$ $\Delta I_L = \frac{(V_{IN} - V_{OUT})}{f_{SW} \times L} \times \frac{V_{OUT}}{V_{IN}}$ $[A]$ $I_P = I_{OUT} + \frac{\Delta I_L}{2}$ $[A]$ $I_V = I_{OUT} - \frac{\Delta I_L}{2}$ $[A]$	V_{IN} : Input voltage $12\ V$ V_{OUT} : Output voltage $5.0\ V$ I_{OUT} : Output current $3.0\ A$ R_{ON-H} : High-side MOSFET on-resistance $100\ m\Omega$ R_{ON-L} : Low-side MOSFET on-resistance $70\ m\Omega$ L : Inductance value $4.7\ \mu H$ f_{SW} : Switching frequency $1.0\ MHz$ t_{r-H} : High-side MOSFET rise time $4\ nsec$ t_{f-H} : High-side MOSFET fall time $6\ nsec$ t_{r-L} : Low-side MOSFET rise time $2\ nsec$ t_{f-L} : Low-side MOSFET fall time $2\ nsec$	$376\ mW$ $369\ mW$
2. Switching-loss $P_{SW-H} = \frac{1}{2} \times V_{IN} \times I_{OUT} \times (t_{r-H} + t_{f-H}) \times f_{SW}$ $[W]$ $P_{SW-L} = \frac{1}{2} \times V_D \times I_{OUT} \times (t_{r-L} + t_{f-L}) \times f_{SW}$ $[W]$	V_D : Forward direction voltage of low-side MOSFET body diode $0.5\ V$ I_{RR} : Peak value of body diode reverse recovery current $0.3\ A$ t_{RR} : Body diode reverse recovery time $25\ \text{nsec}$	$180\ mW$ $3\ mW$
3. Reverse recovery loss $P_{DIODE} = \frac{1}{2} \times V_{IN} \times I_{RR} \times t_{RR} \times f_{SW}$ $[W]$	C_{DS-H} : High-side MOSFET drain-source capacitance $40\ pF$ C_{GD-H} : High-side MOSFET gate-drain capacitance $40\ pF$	$45\ mW$
4. Output capacitance loss in the MOSFET $P_{COSS} = \frac{1}{2} \times C_{OSS-H} \times {V_{IN}}^2 \times f_{SW}$ $[W]$ $C_{OSS-H} = C_{DS-H} + C_{GD-H}$ $[F]$	C_{DS-L} : Low-side MOSFET drain-source capacitance $40\ pF$ C_{GD-L} : Low-side MOSFET gate-drain capacitance $40\ pF$ t_{Dr} : Dead time for rising $30\ nsec$ t_{Df} : Dead time for falling $30\ nsec$	$5.8\ mW$
5. Dead time loss $P_D = V_D \times I_{OUT} \times (t_{Dr} + t_{Df}) \times f_{SW}$ $[W]$	Q_{g-H} : Gate charge of high-side MOSFET $1\ nC$ Q_{g-L} : Gate charge of low-side MOSFET $1\ nC$	$90\ mW$
6. Gate charge loss $P_G = (Q_{g-H} + Q_{g-L}) \times V_{gs} \times f_{SW}$ or $P_G = (C_{GS-H} + C_{GS-L}) \times {V_{gs}}^2 \times f_{SW}$	C_{GS-H} : Gate capacitance of high-side MOSFET $200\ pF$ C_{GS-L} : Gate capacitance of low-side MOSFET $200\ pF$ V_{gs} : Gate drive voltage $5.0V$ I_{CC} : IC current consumption $1.0\ mA$ DCR : Inductor direct current resistance $80\ m\Omega$	$10\ mW$
7. Operation loss caused by the IC $P_{IC} = V_{IN} \times I_{CC}$	ESR_{CIN} : Equivalent series resistance of input capacitor $3\ m\Omega$	$12\ mW$
8. Conduction loss in the inductor $P_{L(DCR)} = \left[{I_{OUT}}^2 + \frac{(I_P - I_V)^2}{12} \right] \times DCR$ $[W]$	ESR_{COUT} : Equivalent series resistance of output capacitor $1\ m\Omega$	$723\ mW$

Calculation example (synchronous rectification type) continued

Calculation formula	Parameters	Result
9. Loss in the capacitor $P_{CIN} = {I_{CIN(RMS)}}^2 \times ESR_{CIN} \quad [W]$ $I_{CIN(RMS)} = I_{OUT} \times \frac{\sqrt{(V_{IN} - V_{OUT}) \times V_{OUT}}}{V_{IN}} \quad [A]$ $P_{COUT} = {I_{COUT(RMS)}}^2 \times ESR_{COUT} \quad [W]$ $I_{COUT(RMS)} = \frac{\Delta I_L}{2\sqrt{3}} \quad [A]$		$6.6\ mW$ $0.5\ mW$
Total power loss $P = P_{ON-H} + P_{ON-L} + P_{SW-H} + P_{SW-L} + P_{DIODE} + P_{COSS} + P_D + P_G + P_{IC} + P_{L(DCR)} + P_{CIN} + P_{COUT} \quad [W]$		$1.82\ W$

Non-synchronous rectification type

Figure 3 shows the circuit diagram of the non-synchronous rectification type. In comparison with the synchronous rectification type in Figure 1, the low-side switch is changed from a MOSFET to a diode. Power loss is mainly caused by the 9 factors listed below. There are some differences in how power loss occurs in synchronous and non-synchronous rectification types. In the synchronous type, conduction loss is caused by the on-resistance of the low-side MOSFET; in the non-synchronous type, conduction loss is caused by the on-resistance of the diode. In the non-synchronous type, there is no switching-loss in the low-side MOSFET. In the synchronous type, there is reverse recovery loss in the low-side MOSFET body diode; in the non-synchronous type, reverse recovery loss occurs in the diode. Finally, in the non-synchronous type, output capacitance loss and gate charge loss occur only in the high-side MOSFET.

1. Conduction loss caused by the on-resistance of the MOSFET P_{ON-H}
2. Conduction loss caused by the on-resistance of the diode P_{ON-D}
3. Switching-loss in the MOSFET P_{SW-H}
4. Reverse recovery loss in the diode P_{DIODE}
5. Output capacitance loss in the MOSFET P_{COSS}
6. Gate charge loss in the MOSFET P_G
7. Operation loss caused by the IC control circuit P_{IC}
8. Conduction loss in the inductor $P_{L(DCR)}$
9. Loss in the capacitor P_{CIN}, P_{COUT}

The calculations are shown for the factors that are different from the synchronous rectification type.

Conduction loss in the diode

While the conduction loss in the MOSFET is determined by the on-resistance, the conduction loss in the diode is determined by the forward direction voltage of the diode and its value becomes large. Since the diode conducts the current when the high-side MOSFET is OFF, the loss can be estimated with the following equation.

$$P_{ON-D} = I_{OUT} \times V_F \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \quad [W] \tag{21}$$

I_{OUT}: Output current $[A]$
V_F: Forward direction voltage of diode $[V]$
V_{IN}: Input voltage $[V]$
V_{OUT}: Output voltage $[V]$

In the case of a buck converter, the on-time of the diode becomes longer as the step-down ratio gets higher or as the output voltage gets lower, resulting in a greater contribution to the power loss of the diode. Therefore, when the output voltage is low, the non-synchronous rectification type is typically less efficient than the synchronous rectification type.

Reverse recovery loss in the diode

The reverse recovery loss in the diode is calculated in the same way as for the body diode of the low-side MOSFET in the synchronous rectification type. When the MOSFET is turned ON, the transition from the forward direction to the reverse bias state of the diode causes a diode recovery, generating a reverse recovery loss in the diode.

This loss is determined by the reverse recovery time of the diode t_{RR}. From the reverse recovery properties of the diode, the loss is calculated with the following equation.

$$P_{DIODE} = \frac{1}{2} \times V_{IN} \times I_{RR} \times t_{RR} \times f_{SW} \quad [W] \tag{22}$$

V_{IN}: Input voltage $[V]$
I_{RR}: Peak value of diode reverse recovery current $[A]$
t_{RR}: Diode reverse recovery time $[sec]$
f_{SW}: Switching frequency $[Hz]$

Output capacitance loss in the MOSFET

In each switching cycle, a loss is generated because the output capacitance of the MOSFET C_{OSS} is charged. This loss can be estimated with the following equation.

$$P_{COSS} = \frac{1}{2} \times (C_{DS-H} + C_{GD-H}) \times V_{IN}^2 \times f_{SW} \quad [W] \tag{23}$$

C_{DS-H}: MOSFET drain-source capacitance $[F]$
C_{GD-H}: MOSFET gate-drain capacitance $[F]$
V_{IN}: Input voltage $[V]$
f_{SW}: Switching frequency $[Hz]$

Gate charge loss

The Gate charge loss is the power loss caused by charging the gate of the MOSFET. The gate charge loss depends on the gate charge (or gate capacitance) of the MOSFET and is calculated with the following equations.

$$P_G = Q_{g-H} \times V_{gs} \times f_{SW} \quad [W] \tag{24}$$

or

$$P_G = C_{GS-H} \times V_{gs}^2 \times f_{SW} \quad [W] \tag{25}$$

Q_{g-H}: Gate charge of MOSFET $[C]$
C_{GS-H}: Gate capacitance of MOSFET $[F]$
V_{gs}: Gate drive voltage $[V]$
f_{SW}: Switching frequency $[Hz]$

Total power loss

The power loss of the IC, *P*, is obtained by adding all the losses together.

$$P = P_{ON-H} + P_{ON-D} + P_{SW-H} + P_{DIODE} + P_{COSS} + P_G + P_{IC} + P_{L(DCR)} + P_{CIN} + P_{COUT} \quad [W] \tag{26}$$

P_{ON-H}: Conduction loss of MOSFET $[W]$
P_{ON-D}: Conduction loss caused by on-resistance of diode $[W]$
P_{SW-H}: Switching-loss of MOSFET $[W]$
P_{DIODE}: Reverse recovery loss of diode $[W]$
P_{COSS}: Output capacitance loss of MOSFET $[W]$
P_G: Gate charge loss of MOSFET $[W]$
P_{IC}: IC operation loss $[W]$
$P_{L(DCR)}$: Conduction loss of inductor $[W]$
P_{CIN}: Input capacitor loss $[W]$
P_{COUT}: Output capacitor loss $[W]$

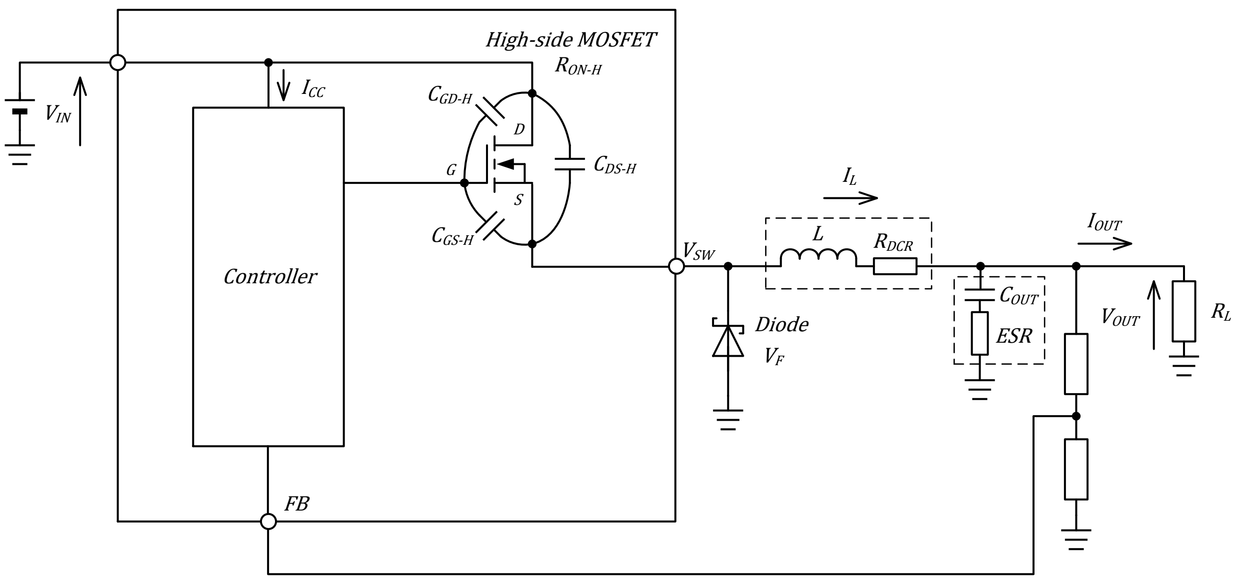


Figure 3. Circuit diagram of the non-synchronous rectification type DC/DC converter

Calculation example (non-synchronous rectification type)

<table>
<tr><th>Calculation formula</th><th>Parameters</th><th>Result</th></tr>
<tr><td>1. Conduction loss in the MOSFET
$$P_{ON-H}=\left[{I_{OUT}}^2+\frac{(I_P-I_V)^2}{12}\right]\times R_{ON-H}\times\frac{V_{OUT}}{V_{IN}}\quad[W]$$
$$\Delta I_L=\frac{(V_{IN}-V_{OUT})}{f_{SW}\times L}\times\frac{V_{OUT}}{V_{IN}}\quad[A]$$
$$I_P=I_{OUT}+\frac{\Delta I_L}{2}\quad[A]$$
$$I_V=I_{OUT}-\frac{\Delta I_L}{2}\quad[A]$$</td><td rowspan="8">V_{IN}： Input voltage $12\ V$
V_{OUT} : Output voltage $5.0\ V$
I_{OUT}： Output current $3.0\ A$
R_{ON-H}： MOSFET on-resistance $100\ m\Omega$
L： Inductance value $4.7\ \mu H$
f_{SW}： Switching frequency $1.0\ MHz$
V_F Forward direction voltage of diode $0.5\ V$
t_{r-H}： MOSFET rise time $4\ nsec$
t_{f-H}： MOSFET fall time $6\ nsec$
I_{RR} : Peak value of diode reverse recovery current $0.3\ A$
t_{RR} : Diode reverse recovery time 25 nsec
C_{DS-H}： MOSFET drain-source capacitance 40 pF
C_{GD-H}： MOSFET gate-drain capacitance 40 pF
Q_{g-H}： Gate charge of MOSFET $1\ nC$
C_{GS-H}： Gate capacitance of MOSFET $200\ pF$
V_{gs}： Gate drive voltage $5.0V$
I_{CC}： IC current consumption $1.0\ mA$
DCR : Inductor direct current resistance $80\ m\Omega$
ESR_{CIN} : :Equivalent series resistance of input capacitor $3\ m\Omega$
ESR_{COUT} : Equivalent series resistance of output capacitor $1\ m\Omega$</td><td>$376\ mW$</td></tr>
<tr><td>2. Conduction loss in the diode
$$P_{ON-D}=I_{OUT}\times V_F\times\left(1-\frac{V_{OUT}}{V_{IN}}\right)\quad[W]$$</td><td>$875\ mW$</td></tr>
<tr><td>3. Switching-loss in the MOSFET
$$P_{SW-H}=\frac{1}{2}\times V_{IN}\times I_{OUT}\times(t_{r-H}+t_{f-H})\times f_{SW}\quad[W]$$</td><td>$180\ mW$</td></tr>
<tr><td>4. Reverse recovery loss in the diode
$$P_{DIODE}=\frac{1}{2}\times V_{IN}\times I_{RR}\times t_{RR}\times f_{SW}\quad[W]$$</td><td>$45\ mW$</td></tr>
<tr><td>5. Output capacitance loss in the MOSFET
$$P_{COSS}=\frac{1}{2}\times(C_{DS-H}+C_{GD-H})\times{V_{IN}}^2\times f_{SW}\quad[W]$$</td><td>$5.8\ mW$</td></tr>
<tr><td>6. Gate charge loss
$$P_G=Q_{g-H}\times V_{gs}\times f_{SW}$$
or
$$P_G=C_{GS-H}\times{V_{gs}}^2\times f_{SW}$$</td><td>$5\ mW$</td></tr>
<tr><td>7. Operation loss caused by the IC
$$P_{IC}=V_{IN}\times I_{CC}$$</td><td>$12\ mW$</td></tr>
<tr><td>8. Conduction loss in the inductor
$$P_{L(DCR)}=\left[{I_{OUT}}^2+\frac{(I_P-I_V)^2}{12}\right]\times DCR\quad[W]$$</td><td>$723\ mW$</td></tr>
</table>

Calculation example (non-synchronous rectification type) continued

Calculation formula	Parameters	Result
9. Loss in the capacitor $P_{CIN} = {I_{CIN(RMS)}}^2 \times ESR_{CIN} \quad [W]$ $I_{CIN(RMS)} = I_{OUT} \times \frac{\sqrt{(V_{IN} - V_{OUT}) \times V_{OUT}}}{V_{IN}} \quad [A]$ $P_{COUT} = {I_{COUT(RMS)}}^2 \times ESR_{COUT} \quad [W]$ $I_{COUT(RMS)} = \frac{\Delta I_L}{2\sqrt{3}} \quad [A]$		$6.6\ mW$ $0.5\ mW$
Total power loss $P = P_{ON-H} + P_{ON-D} + P_{SW-H} + P_{DIODE} + P_{COSS} + P_G + P_{IC} + P_{L(DCR)} + P_{CIN} + P_{COUT} \quad [W]$		$2.23\ W$

Loss factor

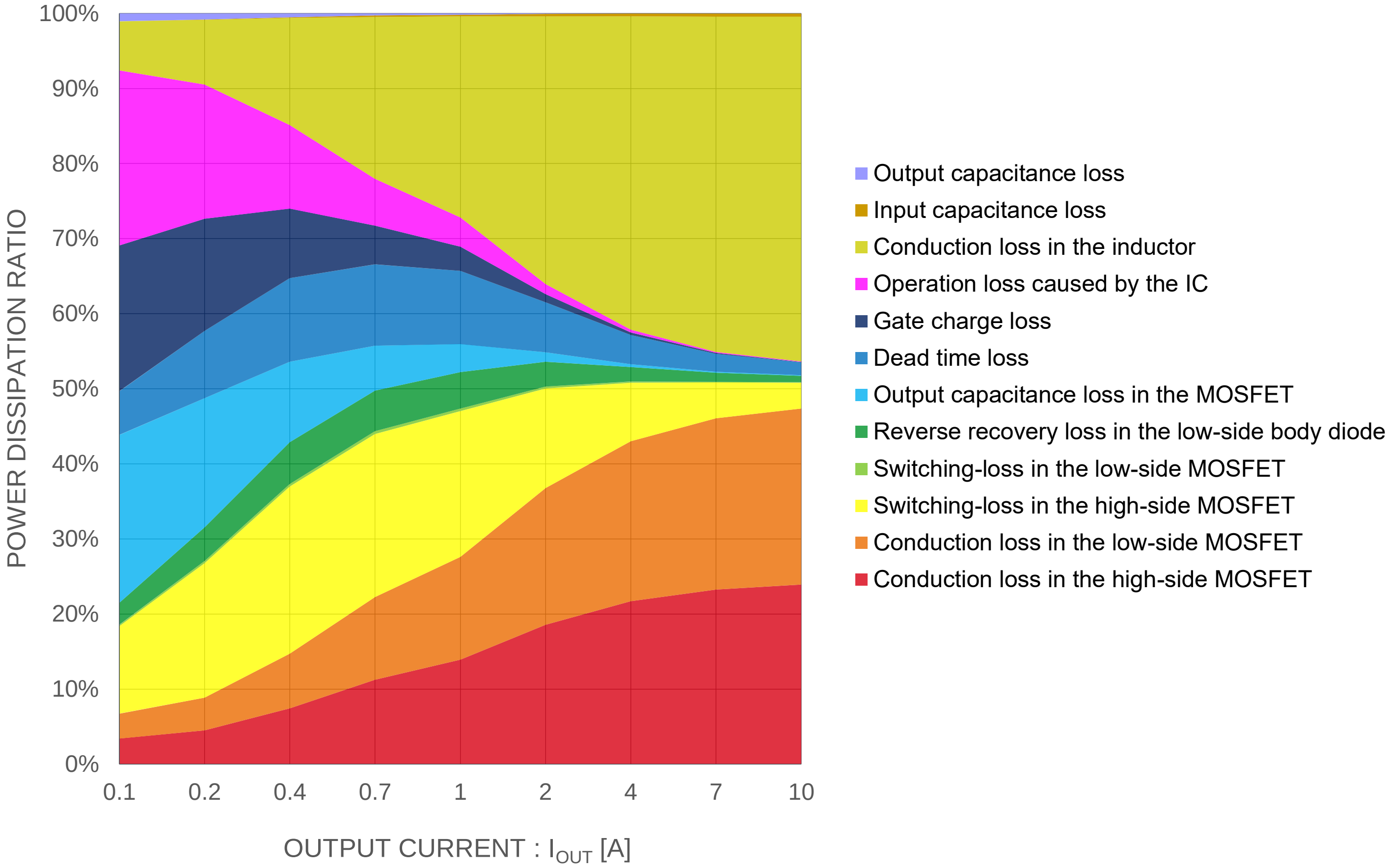
Here we follow how the relative importance of the power loss factors depends on the specification of the switching power source.

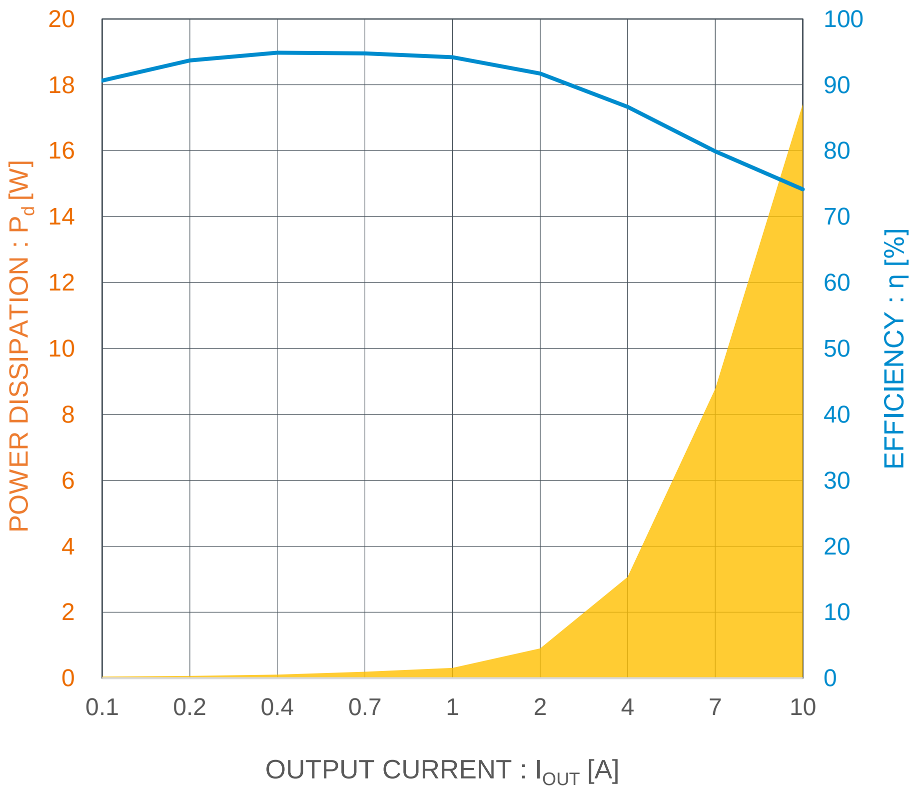
Figure 4 shows the behavior when the output current is varied in the synchronous rectification type. When the current is high, the conduction losses in the MOSFET and the inductor play major roles. This is because the power loss is proportional to the square of the current, as shown in the equations (3), (4), and (14). These losses can be reduced by using MOSFETs with a low on-resistance and by selecting inductors with a low DCR. Since parts with lower conduction resistance are generally larger in size, this selection is a trade-off between conduction loss and size. In addition, the parasitic capacitance describe below typically increases as the MOSFET size increases, causing another trade-off. At low currents, there is a greater impact from the switching-loss in the MOSFET, the output capacitance loss in the MOSFET, the gate charge loss in the MOSFET, and the operation loss of the IC. These MOSFET-related losses are affected mainly by the parasitic capacitance values based on the equations (5), (8), (10), and (11). Although the capacitance value and the loss can be reduced by using a smaller MOSFET, the current capability is also reduced in general, causing a trade-off between the output current value and the size. In addition, since these values are proportional to the switching frequency, the method to reduce the loss by lowering the switching frequency is commonly applied when the current is low. The operation loss caused of the IC can be reduced by optimizing the circuit current in the control circuit.

Figure 5 shows the behavior when the switching frequency is varied in the synchronous rectification type. When operating at high speed, there are increases in the switching-loss in the MOSFET, the reverse recovery loss of the body diode of the MOSFET, the output capacitance loss in the MOSFET, and the dead time loss. Since these MOSFET-related losses increase in proportion to the switching frequency as shown in the equations (5), (7), and (8), it is necessary to select an element that has a low capacitance and that performs switching operations at high speed. As mentioned above, although the capacitance value and the loss can be reduced by using a smaller MOSFET, the current capability is also reduced in general, causing a trade-off between the output current value and the size. To reduce the dead time loss, it is necessary to shorten the dead time by using a design that operates the control circuit at high speed—i.e., by combining the control circuit with a MOSFET that can operate at high speed.

Figure 6 shows the behavior when the output voltage is varied in the synchronous rectification type. This figure illustrates the change in the duty ratio of the switching. To make it easier to understand, the input voltage is set to 10 V, resulting in duty ratios of 10% and 20% for output voltages of 1 V and 2 V, respectively. It is shown that the on-time of the low-side MOSFET becomes longer with a lower duty ratio, increasing the conduction loss in the low-side MOSFET, while the on-time of the high-side MOSFET becomes longer with a higher-duty ratio, increasing the conduction loss in the high-side MOSFET.

Figure 7 shows the same behavior as in Figure 6, with the converter replaced by a non-synchronous type. In comparison with the synchronous type in Figure 6, the conduction loss is greater in the diode that corresponds to the low-side MOSFET in the synchronous type. It is also shown that, when the duty ratio is higher, the difference in the loss between the synchronous and non-synchronous rectification types is smaller, since the on-time of the high-side MOSFET becomes longer. Also, loss in the non-synchronous type become greater as the duty ratio decreases, since the diode on-time becomes longer. To reduce such loss, it is necessary to select parts with diodes that have a lower forward direction voltage.





$V_{IN} = 12V$

$V_{OUT} = 5V$

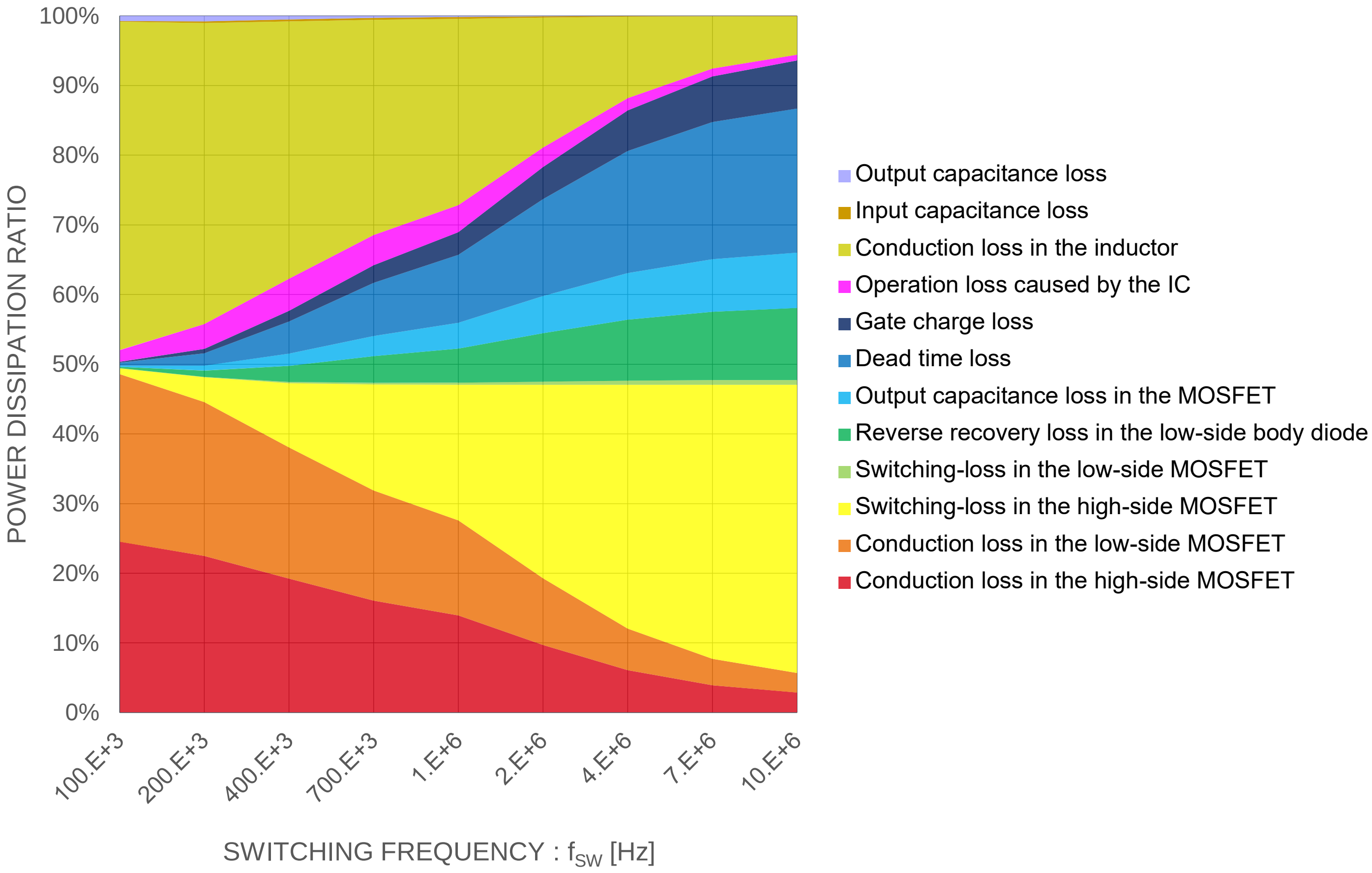
$f_{SW} = 1MHz$

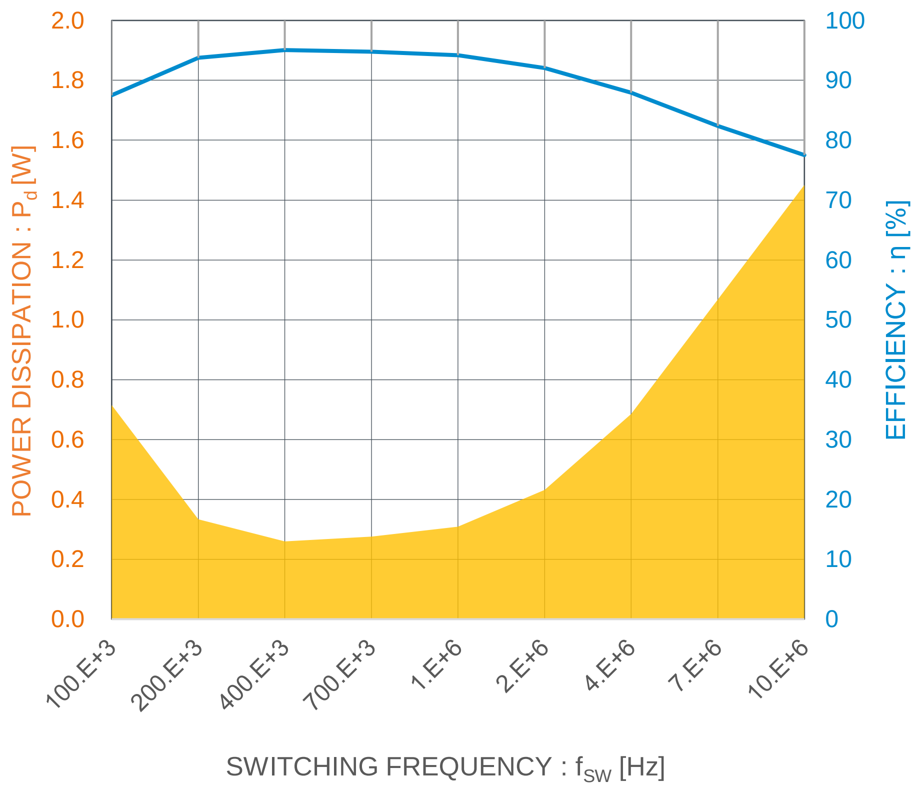
$L = 4.7\mu H$ ($DCR = 80m\Omega$)

High-side MOSFET $R_{ON} = 100m\Omega$

Low-side MOSFET $R_{ON} = 70m\Omega$

Figure 4. Change in loss when output current is varied
(Synchronous rectification type)





$V_{IN} = 12V$

$V_{OUT} = 5V$

$I_O = 1A$

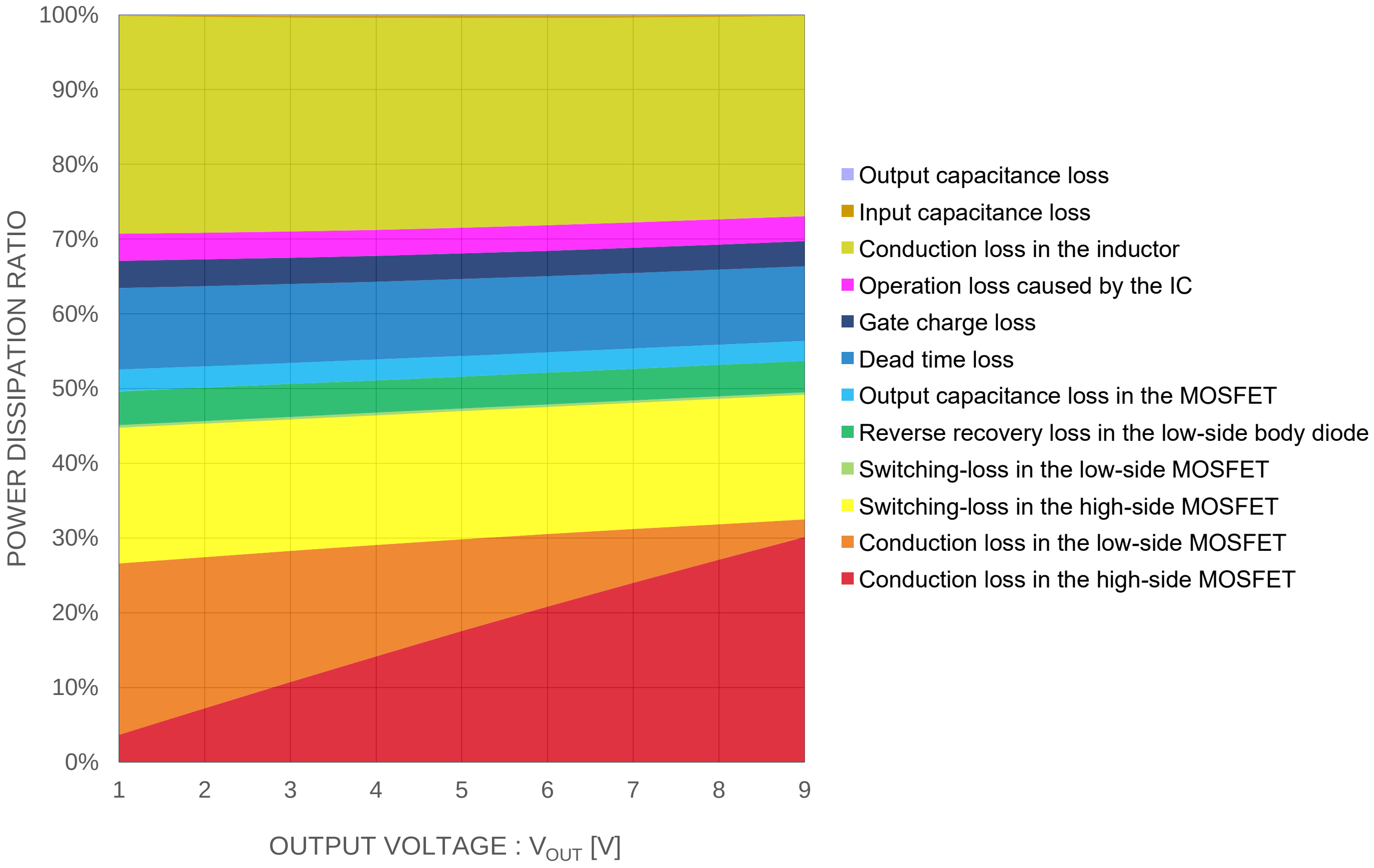
$L = 4.7\mu H$ ($DCR = 80m\Omega$)

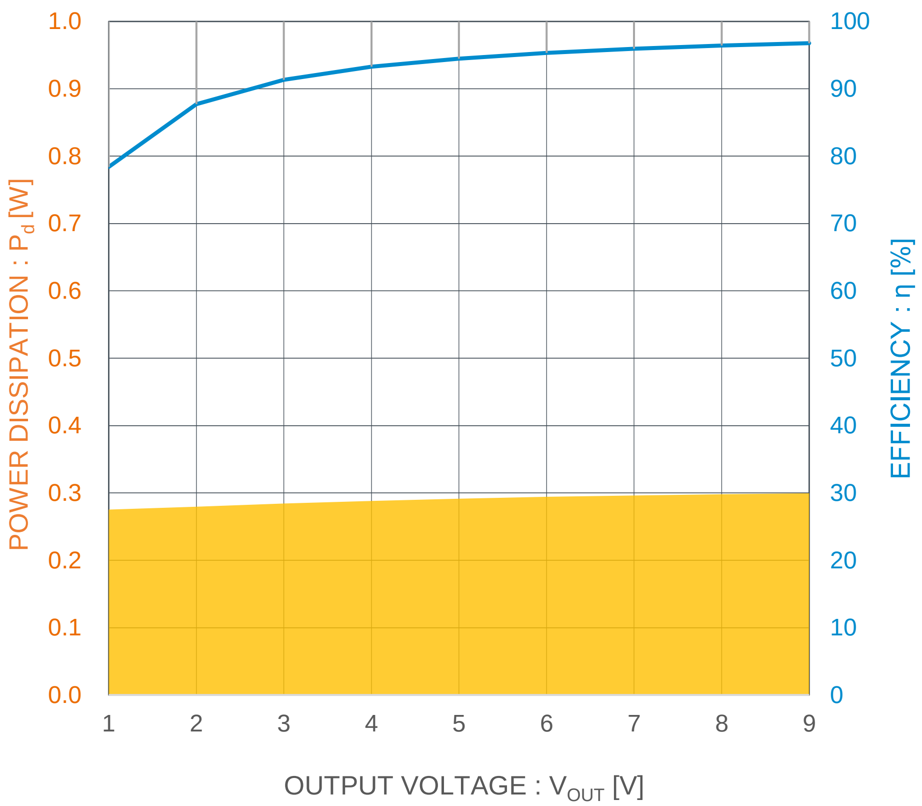
High-side MOSFET $R_{ON} = 100m\Omega$

Low-side MOSFET $R_{ON} = 70m\Omega$

Figure 5. Change in loss when switching frequency is varied

(Synchronous rectification type)





$V_{IN} = 10V$

$I_O = 1A$

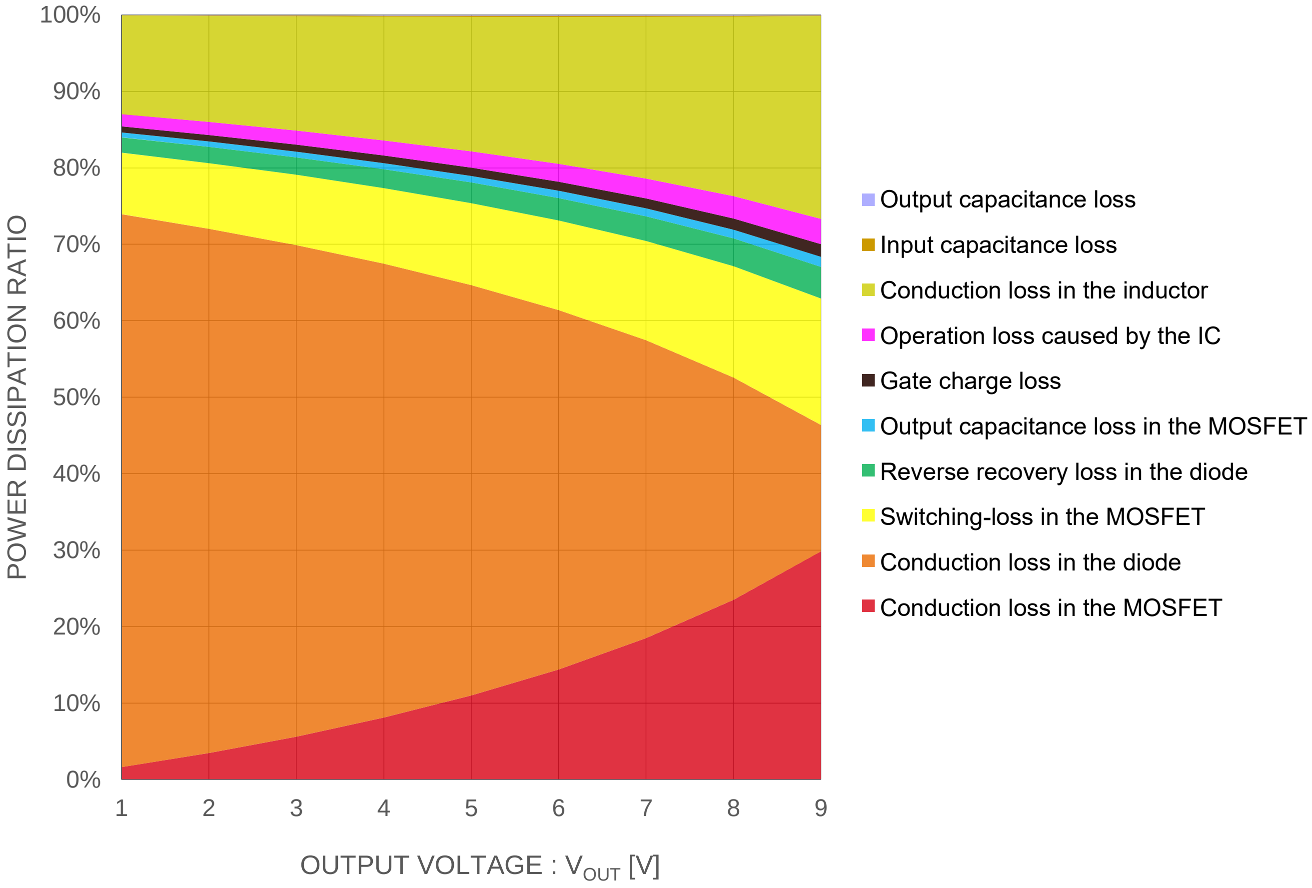
$f_{SW} = 1MHz$

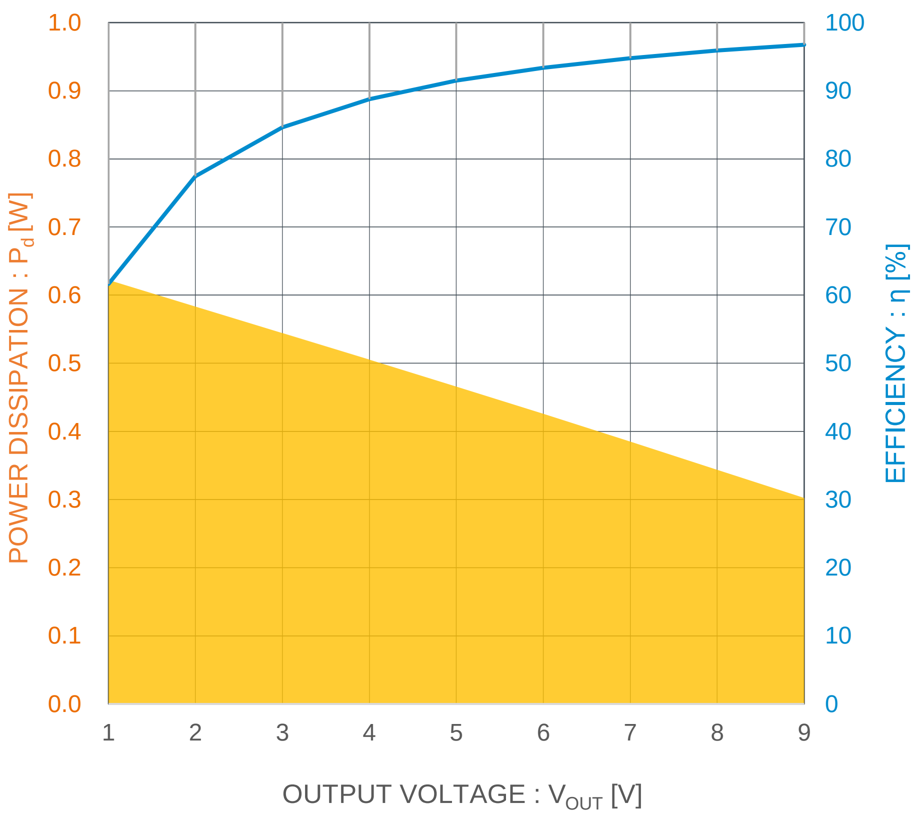
$L = 4.7\mu H$ ($DCR = 80m\Omega$)

High-side MOSFET $R_{ON} = 100m\Omega$

Low-side MOSFET $R_{ON} = 70m\Omega$

Figure 6. Change in loss when output voltage is varied
(Synchronous rectification type)





$V_{IN} = 10V$
$I_O = 1A$
$f_{SW} = 1MHz$
$L = 4.7\mu H\ (DCR = 80m\Omega)$
MOSFET $R_{ON} = 100m\Omega$

Figure 7. Change in loss when output voltage is varied
(Non-synchronous rectification type)

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