Power Device

Calculating Power Loss from Measured Waveforms

This application note describes how to calculate the power loss of a SiC MOSFET from measured switching waveforms in a switching circuit with a SiC MOSFET.

Measurement of switching waveforms

Figure 1 shows a switching circuit and probes for monitoring waveforms. The voltage between the drain and source of the MOSFET is measured using a differential voltage probe. In addition, a current probe is used for the drain current.

Figure 2 shows the waveform of each component and the power loss is shown (shaded area). t_{on} and t_{off} represent the turn on and turn off times, respectively. The switching loss occurs where V_{DS} and I_D overlap in these sections. During the turn ON, since this circuit has an inductance load, I_D starts changing first and then V_{DS} starts changing after the current change is completed. During the turn OFF, on the other hand, V_{DS} starts changing first and then I_D starts changing after the voltage change is completed. Next, T_{ON} is the section where the MOSFET is in an ON state, and conduction loss occurs due to I_D and the on-resistance of the MOSFET.

The latest oscilloscopes may automatically compute the shaded area and display the power loss. However, you need to calculate the power loss from the measured waveforms when using oscilloscopes without this function.

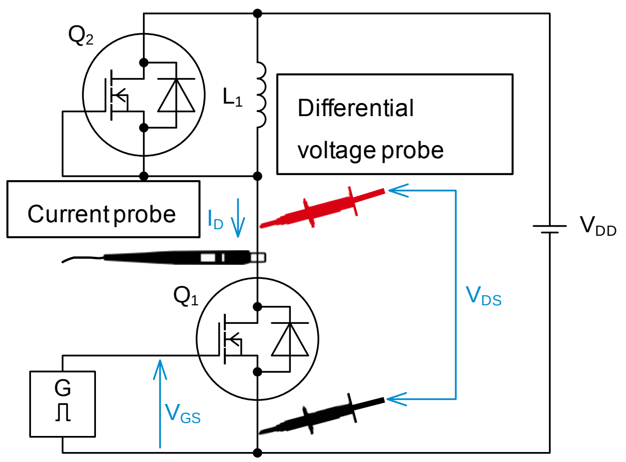


Figure 1. Switching circuit and probes for monitoring waveforms

The following are cautions for the measurement. The first point is the sampling number of the oscilloscope. The detail of the waveforms cannot be captured with an insufficient sampling number, causing an error in the measurement result. It is necessary to display the sampling points and check whether the waveforms are traced accurately. The second point is that, since the characteristics of the delay time are different between the voltage and current probes, the measured waveforms include an error due to this difference in delay. Without correction, deviation is produced along the direction of the time axis between voltage and current, resulting in an incorrect shaded area in Figure 2. This leads to a larger or smaller loss than the actual value, giving erroneous results. To eliminate the difference in delay from the measurement system, it is necessary to perform a skew correction (de-skew). For the method, refer to the instruction manuals of the measuring instruments or the technical materials of the manufacturers of the measuring instruments.

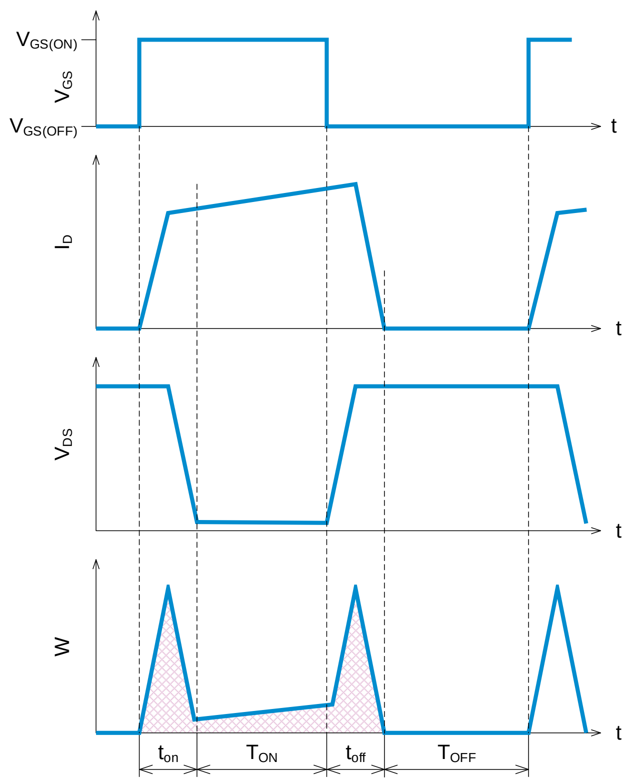


Figure 2. Waveform of each component and power loss (shaded area)

Approximate calculation for waveforms

From the measured waveforms, calculate the power loss by dividing them into sections where a linear approximation can be performed. First, calculate power losses P_{ton} and P_{toff} to be consumed during the turn on and turn off times, respectively. The power loss is calculated with the approximate equations in Table 1. Since the calculation formula depends on waveform shapes, select one that is close to the shape of the measured waveform.

In the example of the waveforms shown in Figure 3, divide the waveforms during the turn ON into two sections, and use case 2 in Table 1 for the former section (t_{on1}). In addition, use the equation under $I_{D1} \coloneqq 0$ as the condition. For the latter section (t_{on2}), use the equation under $V_{DS2} \coloneqq 0$ in case 3. Although voltage is produced by the on-resistance of the MOSFET and I_D in Figure 3, $V_{DS2(on)}$ is treated as 0 if it is sufficiently small relative to the High voltage of V_{DS}. As a result, the power loss during the turn ON can be approximated with the following equation.

$$P_{ton} \approx \frac{1}{2} V_{DS1(on)}\, I_{D2(on)}\, t_{on1}\, f + \frac{1}{6} V_{DS1(on)} \left(2\, I_{D2(on)} + I_{D3(on)}\right) t_{on2}\, f \qquad (1)$$

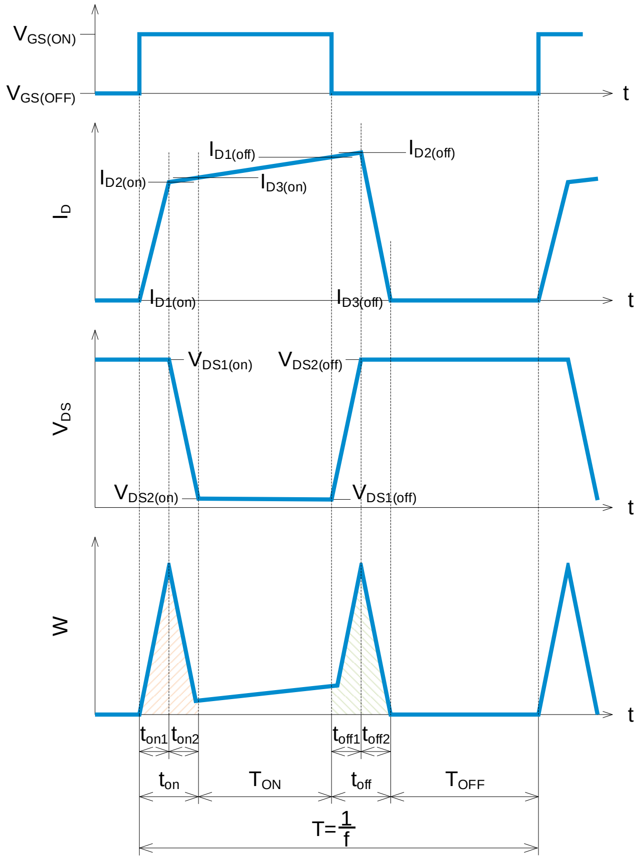


Figure 3. Example of switching loss waveforms

Similarly, divide the waveform during the turn OFF into two sections, and use the equation under $V_{DS1} \coloneqq 0$ in case 1 for the former section (t_{off1}). For the latter section (t_{off2}), use the equation under $I_{D2} \coloneqq 0$ in case 8. Although voltage is produced in Figure 3 for the same reason as mentioned above, $V_{DS1(off)}$ is treated as 0 if it is sufficiently small relative to the High voltage of V_{DS}. As a result, the power loss during the turn OFF can be approximated with the following equation.

$$P_{toff} \approx \frac{1}{6} V_{DS2(off)} \left(I_{D1(off)} + 2\, I_{D2(off)}\right) t_{off1}\, f + \frac{1}{2} V_{DS2(off)}\, I_{D2(off)}\, t_{off2}\, f \qquad (2)$$

Next, calculate the power loss to be consumed during conduction. Figure 4 shows an example of the waveforms to determine the conduction loss. Since the MOSFET is energized in the T_{ON} section, V_{DS} is the product of the on-resistance of the MOSFET and I_D. Refer to the data sheet for the value of the on-resistance. To calculate the power loss, select one of the cases in Table 2 where the shape is close to the waveform and use the approximate equation.

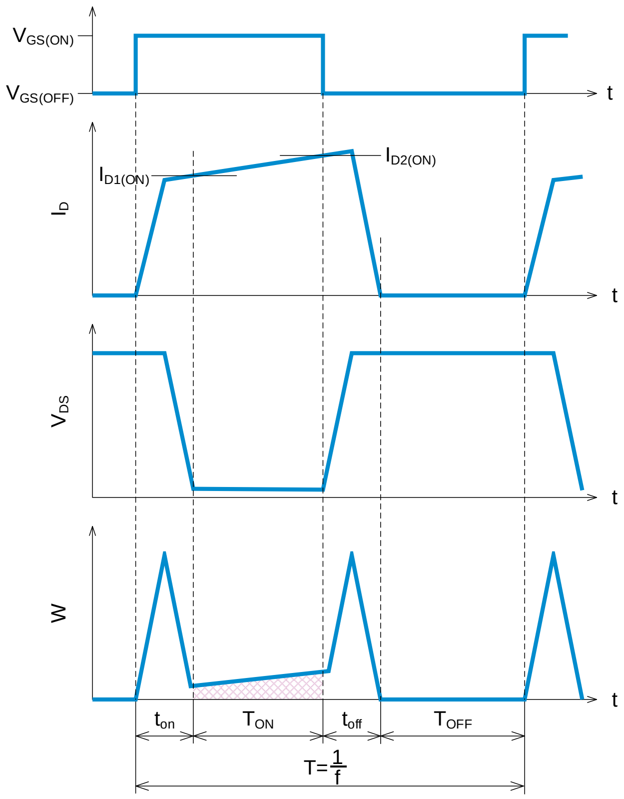


Figure 4. Example of conduction loss waveforms

For this example, case 1 in Table 2 is used. The conduction loss can be calculated with the following equation.

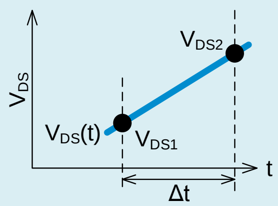
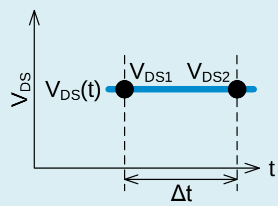
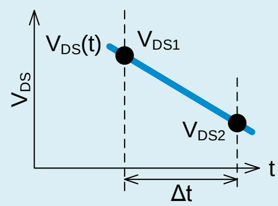
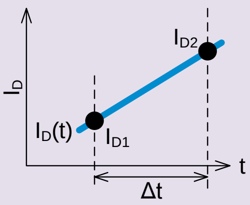
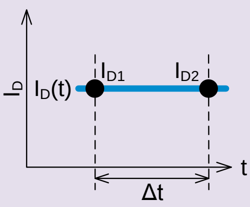
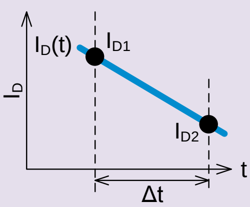
$$P_{ON} \approx \frac{1}{3} R_{ON} \left(I_{D1(ON)}^2 + I_{D1(ON)}\, I_{D2(ON)} + I_{D2(ON)}^2\right) T_{ON}\, f \qquad (3)$$

Next, calculate the power loss when the MOSFET is turned OFF. In Figure 4, the MOSFET is turned OFF in the T_{OFF} section. Since I_D is sufficiently small, the power loss is considered to be 0.

The power loss of the MOSFET is the sum of the power losses calculated so far.

$$P_D = P_{ton} + P_{toff} + P_{ON} \quad [W] \tag{4}$$

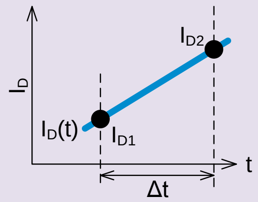
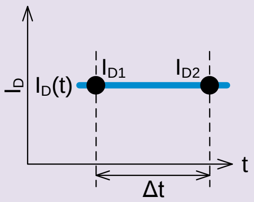
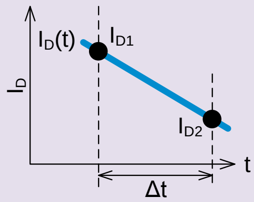
Table 1. Calculation formulas of switching loss using linear approximation for each waveform shape

Variation in I_D with time	Variation in V_{DS} with time		
	$V_{DS1}<V_{DS2}$ 	$V_{DS1}=V_{DS2}$ 	$V_{DS1}>V_{DS2}$ 
$I_{D1}<I_{D2}$ 	Case 1 (see Appendix A) $P \approx$ See $Equation\ (A)\ below$ $V_{DS1} := 0,$ $P \approx \frac{1}{6} V_{DS2} (I_{D1} + 2\, I_{D2})\, \Delta t\, f$ $I_{D1} := 0,$ $P \approx \frac{1}{6} (V_{DS1} + 2\, V_{DS2})\, I_{D2}\, \Delta t\, f$	Case 2 (see Appendix B) $P \approx \frac{1}{2} V_{DS1} (I_{D1} + I_{D2})\, \Delta t\, f \quad (C)$ $I_{D1} := 0,$ $P \approx \frac{1}{2} V_{DS1}\, I_{D2}\, \Delta t\, f$	Case 3 (see Appendix C) $P \approx Equation\ (A)\ below$ $I_{D1} := 0,$ $P \approx \frac{1}{6} (V_{DS1} + 2\, V_{DS2})\, I_{D2}\, \Delta t\, f$ $V_{DS2} := 0,$ $P \approx \frac{1}{6} V_{DS1} (2\, I_{D1} + I_{D2})\, \Delta t\, f$ $I_{D1} := 0, V_{DS2} := 0,$ $P \approx \frac{1}{6} V_{DS1}\, I_{D2}\, \Delta t\, f$
$I_{D1}=I_{D2}$ 	Case 4 (see Appendix D) $P \approx \frac{1}{2} (V_{DS1} + V_{DS2})\, I_{D1}\, \Delta t\, f \quad (B)$ $V_{DS1} := 0,$ $P \approx \frac{1}{2} V_{DS2}\, I_{D1}\, \Delta t\, f$	Case 5 (see Appendix E) $P = V_{DS1}\, I_{D1}\, \Delta t\, f \quad (D)$	Case 6 (see Appendix F) $P \approx \frac{1}{2} (V_{DS1} + V_{DS2})\, I_{D1}\, \Delta t\, f \quad (B)$ $V_{DS2} := 0,$ $P \approx \frac{1}{2} V_{DS1}\, I_{D1}\, \Delta t\, f$
$I_{D1}>I_{D2}$ 	Case 7 (see Appendix G) $P \approx Equation\ (A) below$ $I_{D2} := 0,$ $P \approx \frac{1}{6} (2\, V_{DS1} + V_{DS2})\, I_{D1}\, \Delta t\, f$ $V_{DS1} := 0,$ $P \approx \frac{1}{6} V_{DS2} (I_{D1} + 2\, I_{D2})\, \Delta t\, f$ $I_{D2} := 0, V_{DS1} := 0,$ $P \approx \frac{1}{6} V_{DS2}\, I_{D1}\, \Delta t\, f$	Case 8 (see Appendix H) $P \approx \frac{1}{2} V_{DS1} (I_{D1} + I_{D2})\, \Delta t\, f \quad (C)$ $I_{D2} := 0,$ $P \approx \frac{1}{2} V_{DS1}\, I_{D1}\, \Delta t\, f$	Case 9 (see Appendix I) $P \approx Equation\ (A)\ below$ $V_{DS2} := 0,$ $P \approx \frac{1}{6} V_{DS1} (2\, I_{D1} + I_{D2})\, \Delta t\, f$ $I_{D2} := 0,$ $P \approx \frac{1}{6} (2\, V_{DS1} + V_{DS2})\, I_{D1}\, \Delta t\, f$

$$P \approx \left[\frac{1}{3} (V_{DS1} - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2} I_{D1} (V_{DS1} - V_{DS2}) - \frac{1}{2} V_{DS1} (I_{D1} - I_{D2}) + V_{DS1}\, I_{D1} \right] \Delta t\, f \qquad (A)$$

where, *f*: Switching frequency [Hz]

Table 2. Calculation formulas of conduction loss using linear approximation for each waveform shape

Variation in I_D with time		
$I_{D1}<I_{D2}$ 	$I_{D1}=I_{D2}$ 	$I_{D1}>I_{D2}$ 
Case 1 (see Appendix J)	Case 2 (see Appendix K)	Case 3 (see Appendix L)
$P \approx \frac{1}{3} R_{ON}({I_{D1}}^2 + I_{D1}\, I_{D2} + {I_{D2}}^2)\, \Delta t\, f \quad (\mathrm{E})$	$P = R_{ON}\, {I_{D1}}^2\, \Delta t\, f \quad (F)$	$P \approx \frac{1}{3} R_{ON}({I_{D1}}^2 + I_{D1}\, I_{D2} + {I_{D2}}^2)\, \Delta t\, f \quad (E)$

where, R_{ON}: On-resistance of MOSFET [Ω]

f: Switching frequency [Hz]

Calculation example

Calculate the power loss from the measured switching waveforms (Figure 5). Enlarged waveforms during turn ON, conduction, and turn OFF are shown in Figures 6, 7, and 8, respectively.

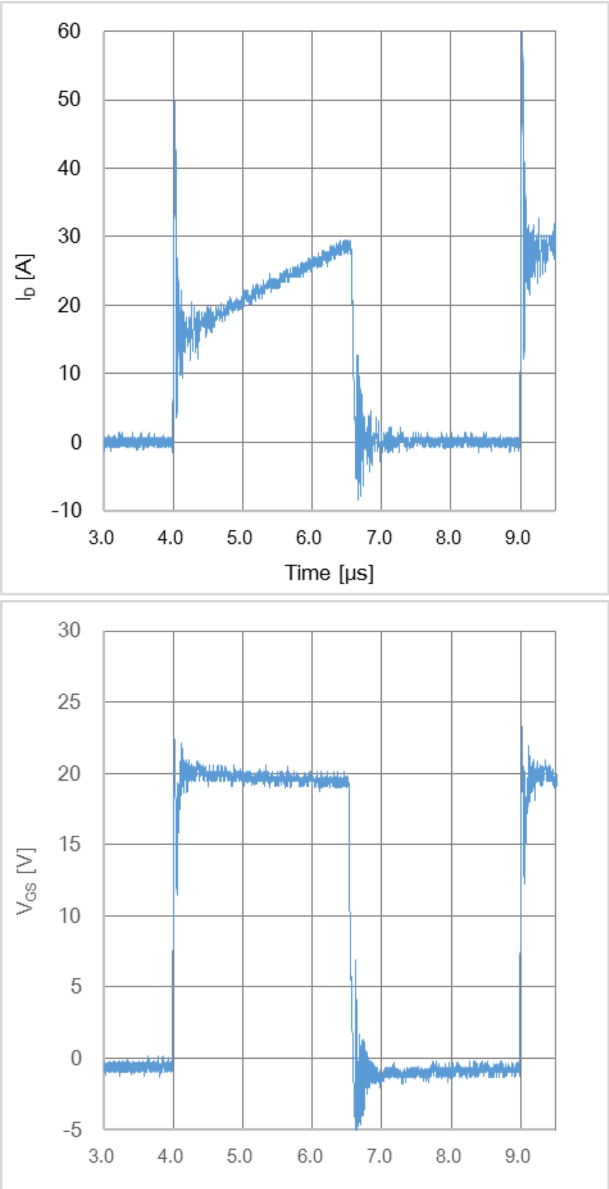


Figure 5. Switching waveforms to be used for power loss calculation

SiC MOSFET SCT3040KR manufactured by ROHM

Switching frequency 200 kHz

Figure 6 shows the enlarged waveforms during the turn ON. Since the slope changes in the middle of the waveforms, divide them into sections with the same slope. However, this division is subjective due to complexity of the waveforms. For each section, read the start voltage and current, the end voltage and current, and the time. Substitute the values into Equation (A) in Table 1 to calculate the power loss.

An example of calculating the power loss during the turn ON is shown below. Here, the waveforms are divided into sections t1 to t5.

$$P_{t1} = \left[\frac{1}{3}(V_{DS1} - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2} I_{D1}(V_{DS1} - V_{DS2}) - \frac{1}{2} V_{DS1}(I_{D1} - I_{D2}) + V_{DS1} I_{D1}\right] \Delta t\, f$$

$$= \left[\frac{1}{3}(800 - 800)(0 - 6.8) - \frac{1}{2} \times 0(800 - 800) - \frac{1}{2} \times 800(0 - 6.8) + 800 \times 0\right] 7.8n \times 200k = 4.2\ [W]$$

$$P_{t2} = \left[\frac{1}{3}(800 - 710)(6.8 - 10.7) - \frac{1}{2} \times 6.8(800 - 710) - \frac{1}{2} \times 800(6.8 - 10.7) + 800 \times 6.8\right] 4.2n \times 200k = 5.5\ [W]$$

$$P_{t3} = \left[\frac{1}{3}(710 - 389)(10.7 - 49.5) - \frac{1}{2} \times 10.7(710 - 389) - \frac{1}{2} \times 710(10.7 - 49.5) + 710 \times 10.7\right] 24.9 \times 200k = 77.2\ [W]$$

$$P_{t4} = \left[\frac{1}{3}(389 - 83)(49.5 - 31.6) - \frac{1}{2} \times 49.5(389 - 83) - \frac{1}{2} \times 389(49.5 - 31.6) + 389 \times 49.5\right] 13n \times 200k = 26.1\ [W]$$

$$P_{t5} = \left[\frac{1}{3}(83 - 18)(31.6 - 8.7) - \frac{1}{2} \times 31.6(83 - 18) - \frac{1}{2} \times 83(31.6 - 8.7) + 83 \times 31.6\right] 7.9n \times 200k = 1.8\ [W]$$

$$\begin{aligned} P_{ton} &= P_{t1} + P_{t2} + P_{t3} + P_{t4} + P_{t5} \\ &= 4.2 + 5.5 + 77.2 + 26.1 + 1.8 \\ &= 114.8\ [W] \end{aligned}$$

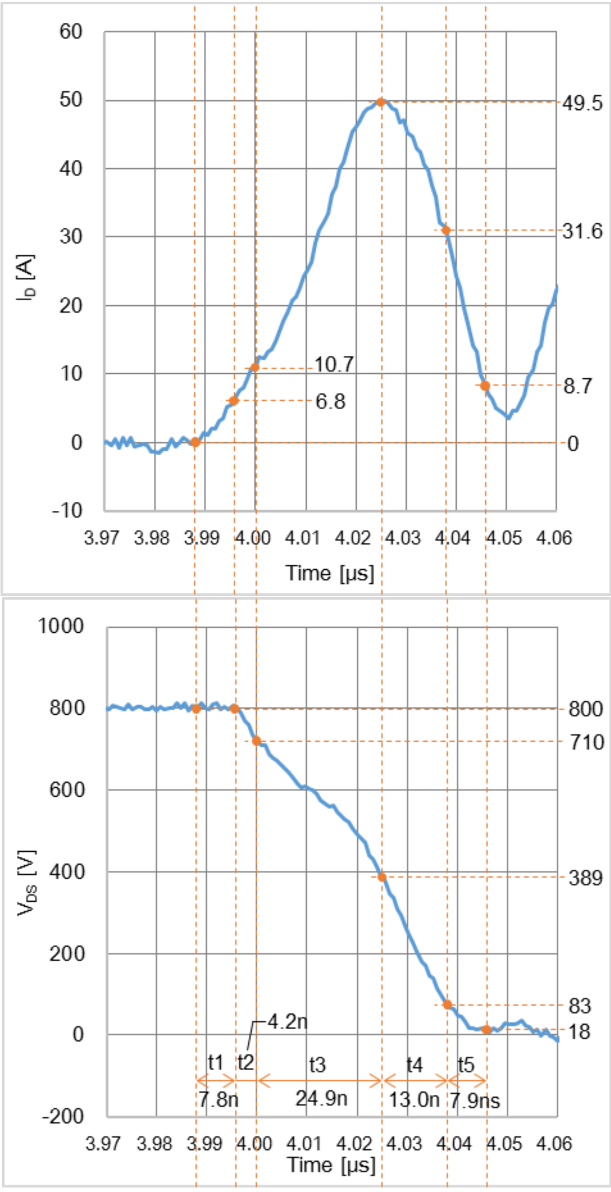


Figure 6. Enlarged waveforms and measured values in each section during turn ON

Figure 7 shows the enlarged waveforms during conduction. Here, substitute the values into Equation (E) in Table 1 to calculate the power loss. For the on-resistance of the MOSFET, use the maximum value from the data sheet.

$$P_{ON} = \frac{1}{3} R_{ON}({I_{D1}}^2 + I_{D1}\, I_{D2} + {I_{D2}}^2)\ \Delta t\ f$$

$$= \frac{1}{3} \times\ 68\, m(15^2 +\ 15\ \times\ 28.7\ + 28.7^2) 2.49\mu\ \times\ 200k$$

$$= 16.7\ [W]$$

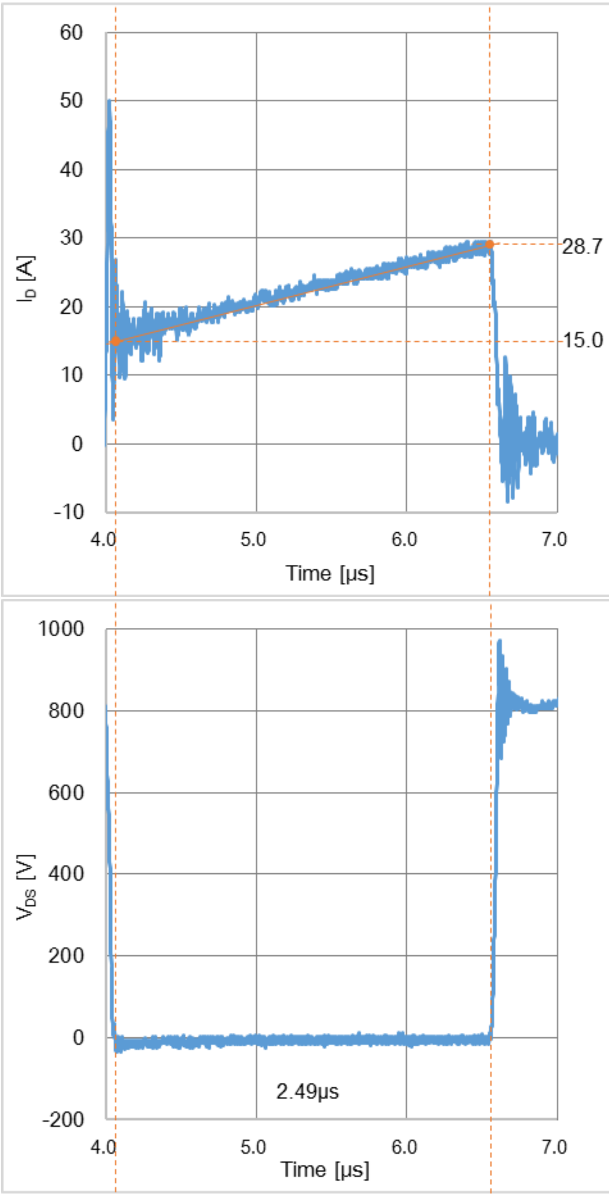


Figure 7. Enlarged waveforms and measured values during conduction

Figure 8 shows the enlarged waveforms during the turn OFF. The power loss is calculated with the same procedure as during the turn ON.

An example of calculating the power loss during the turn OFF is shown below. Here, the waveforms are divided into sections t1 to t8.

$P_{t1} = 1.5\ [W]$ $\quad P_{t2} = 9.3\ [W]$

$P_{t3} = 9.9\ [W]$ $\quad P_{t4} = 14.6\ [W]$

$P_{t5} = 7.8\ [W]$ $\quad P_{t6} = 7.0\ [W]$

$P_{t7} = 8.0\ [W]$ $\quad P_{t8} = 5.7\ [W]$

$$P_{toff} = 1.5 + 9.3 + 9.9 + 14.6 + 7.8 + 7 + 8 + 5.7 = 63.8\ [W]$$

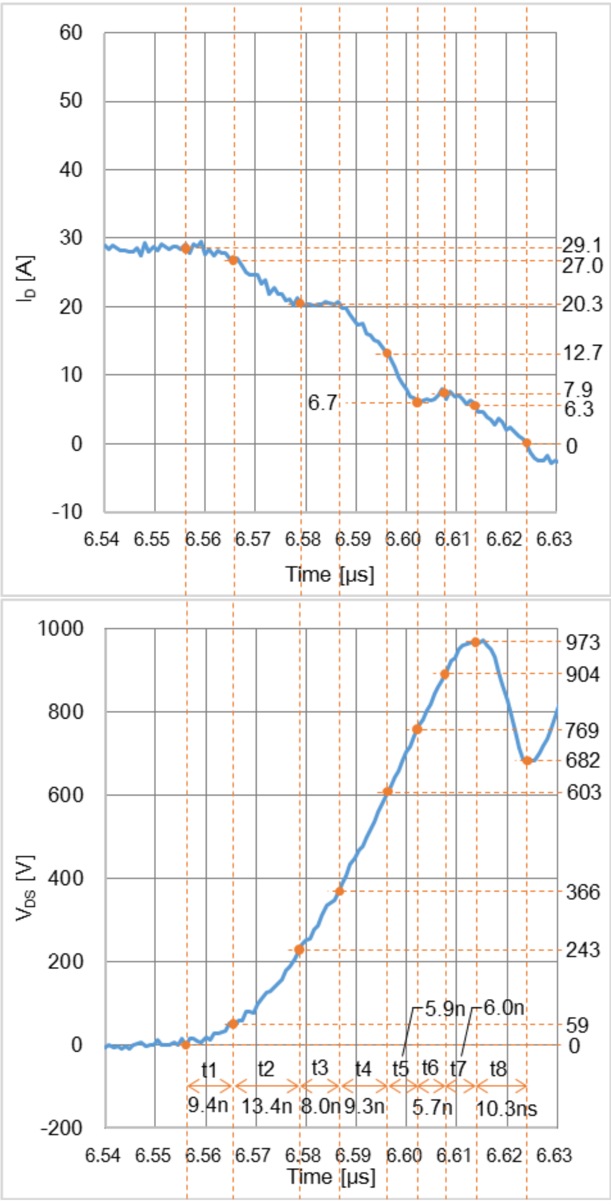


Figure 8. Enlarged waveforms and measured values in each section during turn OFF

The total power loss can be calculated with the following equation.

$$\begin{aligned} \mathrm{P} &= P_{ton} + P_{ON} + P_{toff} \\ &= 114.8 + 16.7 + 63.8 \\ &= 195.3\ [W] \end{aligned}$$

Appendix A

Calculation of switching loss (when the waveforms of I_D and V_{DS} are increasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure A-1.

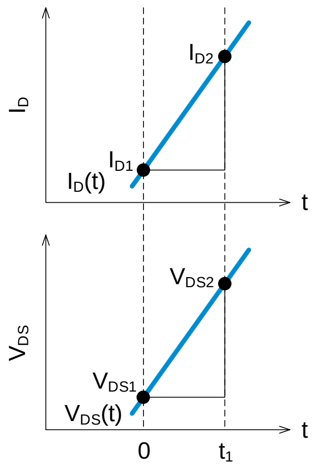


Figure A-1. I_D(t) and V_{DS}(t) in period 0-t_1

Power loss P in period 0-t_1 shown in Figure A-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (A-1).

$$P = f\int_0^{t_1} I_D(t)\,V_{DS}(t)\,dt \qquad (A-1)$$

where, *f*: Switching frequency [Hz]

In addition, I_D(t) and V_{DS}(t) can be represented with Equations (A-2) and (A-3) from the slopes in Figure A-1.

$$I_D(t) = I_{D1} + \frac{I_{D2}-I_{D1}}{t_1}t = I_{D1} - \frac{I_{D1}-I_{D2}}{t_1}t \qquad (A-2)$$

$$V_{DS}(t) = V_{DS1} + \frac{V_{DS2}-V_{DS1}}{t_1}t = V_{DS1} - \frac{V_{DS1}-V_{DS2}}{t_1}t \qquad (A-3)$$

Substitute (A-2) and (A-3) into (A-1).

$$P = f\int_0^{t_1}\left(I_{D1} - \frac{I_{D1}-I_{D2}}{t_1}t\right)\left(V_{DS1} - \frac{V_{DS1}-V_{DS2}}{t_1}t\right)dt \qquad (A-4)$$

$$= f\int_0^{t_1}\left(V_{DS1}\,I_{D1} - \frac{I_{D1}(V_{DS1}-V_{DS2})+V_{DS1}(I_{D1}-I_{D2})}{t_1}t + \frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2}t^2\right)dt \qquad (A-5)$$

Appendix A (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\, I_{D1}\, t - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})}{t_1} t^2 + \frac{1}{3}\frac{(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})}{t_1^2} t^3\right]_0^{t_1} \qquad (A-6)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})}{t_1} t_1^2 + \frac{1}{3}\frac{(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})}{t_1^2} t_1^3\right] \qquad (A-7)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\big(I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})\big)t_1 + \frac{1}{3}(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})t_1\right] \qquad (A-8)$$

$$= \left[\frac{1}{3}(V_{DS1} - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2}I_{D1}(V_{DS1} - V_{DS2}) - \frac{1}{2}V_{DS1}(I_{D1} - I_{D2}) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad [W] \qquad (A-9)$$

where, f: Switching frequency [Hz]

Next, calculate the power loss under the conditions below.

$$V_{DS1} \coloneqq 0 \qquad (A-10)$$

Substitute (A-10) into (A-9).

$$P = \left[\frac{1}{3}(0 - V_{DS2})(I_{D1} - I_{D2}) - \frac{1}{2}I_{D1}(0 - V_{DS2}) - \frac{1}{2}\times 0(I_{D1} - I_{D2}) + 0 \times I_{D1}\right] t_1\, f \qquad (A-11)$$

$$= \left[-\frac{1}{3}V_{DS2}(I_{D1} - I_{D2}) + \frac{1}{2}I_{D1}\, V_{DS2}\right] t_1\, f \qquad (A-12)$$

$$= \frac{1}{6}V_{DS2}(I_{D1} + 2\, I_{D2})t_1\, f \qquad [W] \qquad (A-13)$$

$$I_{D1} \coloneqq 0 \qquad (A-14)$$

Substitute (A-14) into (A-9).

$$P = \left[\frac{1}{3}(V_{DS1} - V_{DS2})(0 - I_{D2}) - \frac{1}{2}\times 0(V_{DS1} - V_{DS2}) - \frac{1}{2}V_{DS1}(0 - I_{D2}) + V_{DS1} \times 0\right] t_1\, f \qquad (A-15)$$

$$= \left[\frac{1}{3}(V_{DS1} - V_{DS2})(-I_{D2}) + \frac{1}{2}V_{DS1}\, I_{D2}\right] t_1\, f \qquad (A-16)$$

$$= \frac{1}{6}(V_{DS1} + 2\, V_{DS2})\, I_{D2}\, t_1\, f \qquad [W] \qquad (A-17)$$

Appendix B

Calculation of switching loss (when the waveform of I_D is increasing and V_{DS} constant)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure B-1.

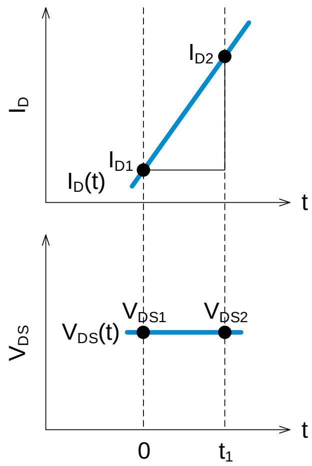


Figure B-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure B-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (B-1).

$$P = f\int_0^{t_1} I_D(t)\,V_{DS}(t)\,dt \qquad (B-1)$$

where, *f*: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (B-2) and (B-3) from the slopes in Figure B-1.

$$I_D(t) = I_{D1} + \frac{I_{D2} - I_{D1}}{t_1}t = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t \qquad (B-2)$$

$$V_{DS}(t) = V_{DS1} \qquad (B-3)$$

Substitute (B-2) and (B-3) into (B-1).

$$P = f\int_0^{t_1}\left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t\right)(V_{DS1})dt \qquad (B-4)$$

$$= f\int_0^{t_1}\left(V_{DS1}I_{D1} - \frac{V_{DS1}(I_{D1} - I_{D2})}{t_1}t\right)dt \qquad (B-5)$$

Appendix B (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\,I_{D1}t - \frac{1}{2}\frac{V_{DS1}(I_{D1} - I_{D2})}{t_1}t^2\right]_0^{t_1} \qquad (B-6)$$

$$= f\left[V_{DS1}\,I_{D1}\,t_1 - \frac{1}{2}\frac{V_{DS1}(I_{D1} - I_{D2})}{t_1}t_1^2\right] \qquad (B-7)$$

$$= f\left[V_{DS1}\,I_{D1}\,t_1 - \frac{1}{2}\left(V_{DS1}(I_{D1} - I_{D2})\right)t_1\right] \qquad (B-8)$$

$$= \frac{1}{2}V_{DS1}(I_{D1} + I_{D2})\,t_1\,f \qquad [W] \qquad (B-9)$$

Next, calculate the power loss under the conditions below.

$$I_{D1} \coloneqq 0 \qquad (B-10)$$

Substitute (B-10) into (B-9).

$$P = \frac{1}{2}V_{DS1}\,I_{D2}\,t_1\,f \qquad [W] \qquad (B-11)$$

Appendix C

Calculation of switching loss (when the waveform of I_D is increasing and V_{DS} decreasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure C-1.

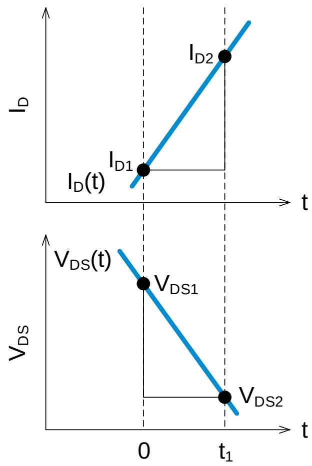


Figure C-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure C-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (C-1).

$$P = f\int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (C-1)$$

where, *f*: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (C-2) and (C-3) from the slopes in Figure C-1.

$$I_D(t) = I_{D1} + \frac{I_{D2} - I_{D1}}{t_1} t = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t \qquad (C-2)$$

$$V_{DS}(t) = V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t \qquad (C-3)$$

Substitute (C-2) and (C-3) into (C-1).

$$P = f\int_0^{t_1} \left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t\right)\left(V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t\right) dt \qquad (C-4)$$

$$= f\int_0^{t_1} \left(V_{DS1}\, I_{D1} - \frac{I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})}{t_1} t + \frac{(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})}{t_1^2} t^2\right) dt \qquad (C-5)$$

Appendix C (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\,I_{D1}\,t - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1}t^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2}t^3\right]_0^{t_1} \qquad (C-6)$$

$$= f\left[V_{DS1}\,I_{D1}t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1}t_1^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2}t_1^3\right] \qquad (C-7)$$

$$= f\left[V_{DS1}\,I_{D1}t_1 - \frac{1}{2}\big(I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})\big)t_1 + \frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})t_1\right] \qquad (C-8)$$

$$= \left[\frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\,I_{D1}\right]t_1\,f \qquad [W] \qquad (C-9)$$

Next, calculate the power loss under the conditions below.

$$\underline{I_{D1} \coloneqq 0} \qquad (C-10)$$

Substitute (C-10) into (C-9).

$$P = \left[\frac{1}{3}(V_{DS1}-V_{DS2})(0-I_{D2}) - \frac{1}{2}\times 0(V_{DS1}-V_{DS2}) - \frac{1}{2}V_{DS1}(0-I_{D2}) + V_{DS1}\times 0\right]t_1\,f \qquad (C-11)$$

$$= \left[\frac{1}{3}(V_{DS1}-V_{DS2})(-I_{D2}) + \frac{1}{2}V_{DS1}\,I_{D2}\right]t_1\,f \qquad (C-12)$$

$$= \frac{1}{6}(V_{DS1} + 2\,V_{DS2})I_{D2}\;t_1\,f \qquad [W] \qquad (C-13)$$

$$\underline{V_{DS2} \coloneqq 0} \qquad (C-14)$$

Substitute (C-14) into (C-9).

$$P = \left[\frac{1}{3}(V_{DS1}-0)(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}(V_{DS1}-0) - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\,I_{D1}\right]t_1\,f \qquad (C-15)$$

$$= \left[\frac{1}{3}V_{DS1}(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}\,V_{DS1} - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\,I_{D1}\right]t_1\,f \qquad (C-16)$$

$$= \frac{1}{6}V_{DS1}(2\,I_{D1} + I_{D2})\;t_1\,f \qquad [W] \qquad (C-17)$$

$$\underline{I_{D1} \coloneqq 0,\;\; V_{DS2} \coloneqq 0} \qquad (C-18)$$

Substitute (C-18) into (C-9).

$$P = \left[\frac{1}{3}(V_{DS1}-0)(0-I_{D2}) - \frac{1}{2}\times 0(V_{DS1}-0) - \frac{1}{2}V_{DS1}(0-I_{D2}) + V_{DS1}\times 0\right]t_1\,f \qquad (C-19)$$

$$= \left[\frac{1}{3}V_{DS1}(-I_{D2}) - \frac{1}{2}V_{DS1}(-I_{D2})\right]t_1\,f \qquad (C-20)$$

$$= \frac{1}{6}V_{DS1}\,I_{D2}\;t_1\,f \qquad [W] \qquad (C-21)$$

Appendix D

Calculation of switching loss (when the waveform of I_D is constant and V_{DS} increasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure D-1.

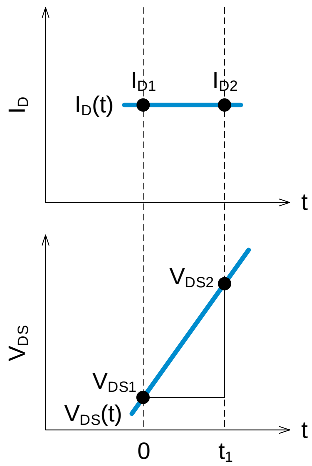


Figure D-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure D-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (D-1).

$$P = f \int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (D-1)$$

where, f: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (D-2) and (D-3) from the slopes in Figure D-1.

$$I_D(t) = I_{D1} \qquad (D-2)$$

$$V_{DS}(t) = V_{DS1} + \frac{V_{DS2} - V_{DS1}}{t_1} t = V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t \qquad (D-3)$$

Substitute (D-2) and (D-3) into (D-1).

$$P = f \int_0^{t_1} I_{D1} \left(V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t \right) dt \qquad (D-4)$$

$$= f \int_0^{t_1} \left(V_{DS1}\, I_{D1} - \frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t \right) dt \qquad (D-5)$$

Appendix D (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\, I_{D1}\, t - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t^2\right]_0^{t_1} \qquad (D-6)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t_1^2\right] \qquad (D-7)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\left(I_{D1}(V_{DS1} - V_{DS2})\right)t_1\right] \qquad (D-8)$$

$$= \frac{1}{2}(V_{DS1} + V_{DS2})\, I_{D1}\, t_1\, f \qquad [W] \qquad (D-9)$$

Next, calculate the power loss under the conditions below.

$$V_{DS1} \coloneqq 0 \qquad (D-10)$$

Substitute (D-10) into (D-9).

$$P = \frac{1}{2}(0 + V_{DS2})\, I_{D1}\, t_1\, f \qquad (D-11)$$

$$= \frac{1}{2} V_{DS2}\, I_{D1}\, t_1\, f \qquad [W] \qquad (D-12)$$

Appendix E

Calculation of switching loss (when I_D and V_{DS} are constant)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure E-1.

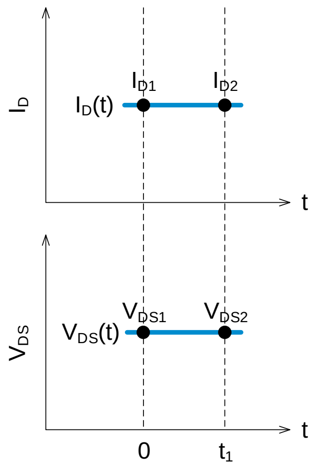


Figure E-1. I_D(t) and V_{DS}(t) in period 0-t_1

Power loss P in period 0-t_1 shown in Figure E-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (E-1).

$$P = f \int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (E-1)$$

where, f: Switching frequency [Hz]

In addition, I_D(t) and V_{DS}(t) can be represented with Equations (E-2) and (E-3) from the slopes in Figure E-1.

$$I_D(t) = I_{D1} \qquad (E-2)$$

$$V_{DS}(t) = V_{DS1} \qquad (E-3)$$

Substitute (E-2) and (E-3) into (E-1).

$$P = f \int_0^{t_1} I_{D1}\, V_{DS1}\, dt \qquad (E-4)$$

Perform the integration according to the formula.

$$P = f\, [V_{DS1}\, I_{D1}\, t]_0^{t_1} \qquad (E-5)$$

$$= V_{DS1}\, I_{D1}\, t_1\, f \qquad [W] \qquad (E-6)$$

Appendix F

Calculation of switching loss (when the waveform of I_D is constant and V_{DS} decreasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure F-1.

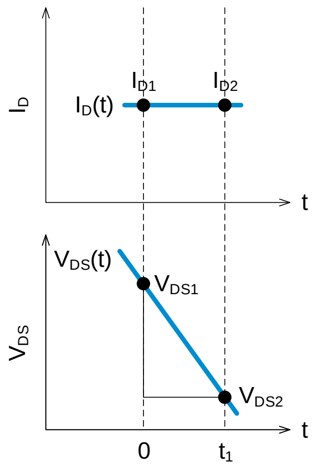


Figure F-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure F-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (F-1).

$$P = f\int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (F-1)$$

where, f: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (F-2) and (F-3) from the slopes in Figure F-1.

$$I_D(t) = I_{D1} \qquad (F-2)$$

$$V_{DS}(t) = V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t \qquad (F-3)$$

Substitute (F-2) and (F-3) into (F-1).

$$P = f\int_0^{t_1} I_{D1}\left(V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t\right) dt \qquad (F-4)$$

$$= f\int_0^{t_1}\left(V_{DS1}\, I_{D1} - \frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t\right) dt \qquad (F-5)$$

Appendix F (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\, I_{D1}\, t - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t^2\right]_0^{t_1} \qquad (F-6)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1} - V_{DS2})}{t_1} t_1^2\right] \qquad (F-7)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\left(I_{D1}(V_{DS1} - V_{DS2})\right)t_1\right] \qquad (F-8)$$

$$\underline{= \frac{1}{2}(V_{DS1} + V_{DS2})\, I_{D1}\, t_1\, f \qquad [W]} \qquad (F-9)$$

Next, calculate the power loss under the conditions below.

$$\underline{V_{DS2} \coloneqq 0} \qquad (\mathrm{F}-10)$$

Substitute (F-10) into (F-9).

$$P = \frac{1}{2}(V_{DS1} + 0)\, I_{D1}\, t_1\, f \qquad (F-11)$$

$$\underline{= \frac{1}{2} V_{DS1}\, I_{D1}\, t_1\, f \qquad [W]} \qquad (F-12)$$

Appendix G

Calculation of switching loss (when the waveform of I_D is decreasing and V_{DS} increasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure G-1.

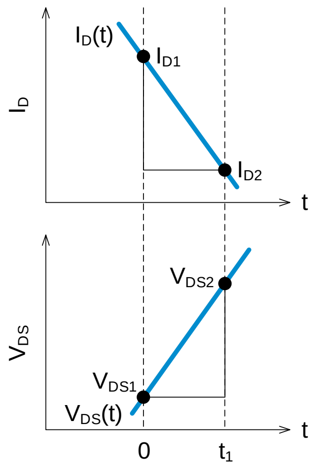


Figure G-1. I_D(t) and V_{DS}(t) in period 0-t_1

Power loss P in period 0-t_1 shown in Figure G-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (G-1).

$$P = f\int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (G-1)$$

where, *f*: Switching frequency [Hz]

In addition, I_D(t) and V_{DS}(t) can be represented with Equations (G-2) and (G-3) from the slopes in Figure G-1.

$$I_D(t) = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t \qquad (G-2)$$

$$V_{DS}(t) = V_{DS1} + \frac{V_{DS2} - V_{DS1}}{t_1} t = V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t \qquad (G-3)$$

Substitute (G-2) and (G-3) into (G-1).

$$P = f\int_0^{t_1} \left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t\right)\left(V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1} t\right) dt \qquad (G-4)$$

$$= f\int_0^{t_1} \left(V_{DS1}\, I_{D1} - \frac{I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})}{t_1} t + \frac{(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})}{t_1^2} t^2\right) dt \qquad (G-5)$$

Appendix G (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\, I_{D1} t - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1} t^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2} t^3\right]_0^{t_1} \qquad (G-6)$$

$$= f\left[V_{DS1}\, I_{D1} t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1} t_1^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2} t_1^3\right] \qquad (G-7)$$

$$= f\left[V_{DS1}\, I_{D1} t_1 - \frac{1}{2}\left(I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})\right) t_1 + \frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2}) t_1\right] \qquad (G-8)$$

$$\underline{= \left[\frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2}) - \frac{1}{2} I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2} V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad [W]} \qquad (G-9)$$

Next, calculate the power loss under the conditions below.

$$\underline{I_{D2} \coloneqq 0} \qquad (G-10)$$

Substitute (G-10) into (G-9).

$$P = \left[\frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-0) - \frac{1}{2} I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2} V_{DS1}(I_{D1}-0) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (G-11)$$

$$= \left[\frac{1}{3}(V_{DS1}-V_{DS2})\, I_{D1} - \frac{1}{2} I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2} V_{DS1}\, I_{D1} + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (G-12)$$

$$\underline{= \frac{1}{6}(2\, V_{DS1} + V_{DS2})\, I_{D1}\, t_1\, f \qquad [W]} \qquad (G-13)$$

$$\underline{V_{DS1} \coloneqq 0} \qquad (G-14)$$

Substitute (G-14) into (G-9).

$$P = \left[\frac{1}{3}(0-V_{DS2})(I_{D1}-I_{D2}) - \frac{1}{2} I_{D1}(0-V_{DS2}) - \frac{1}{2}\times 0(I_{D1}-I_{D2}) + 0\times I_{D1}\right] t_1\, f \qquad (G-15)$$

$$= \left[-\frac{1}{3} V_{DS2}(I_{D1}-I_{D2}) + \frac{1}{2} I_{D1}\, V_{DS2}\right] t_1\, f \qquad (G-16)$$

$$\underline{= \frac{1}{6} V_{DS2}(I_{D1} + 2\, I_{D2})\, t_1\, f \qquad [W]} \qquad (G-17)$$

$$\underline{I_{D2} \coloneqq 0,\ \ V_{DS1} \coloneqq 0} \qquad (G-18)$$

Substitute (G-18) into (G-9).

$$P = \left[\frac{1}{3}(0-V_{DS2})(I_{D1}-0) - \frac{1}{2} I_{D1}(0-V_{DS2}) - \frac{1}{2}\times 0(I_{D1}-0) + 0 \times I_{D1}\right] t_1\, f \qquad (G-19)$$

$$= \left(-\frac{1}{3} V_{DS2}\, I_{D1} + \frac{1}{2} I_{D1}\, V_{DS2}\right) t_1\, f \qquad (G-20)$$

$$\underline{= \frac{1}{6} V_{DS2}\, I_{D1}\, t_1\, f \qquad [W]} \qquad (G-21)$$

Appendix H

Calculation of switching loss (when the waveform of I_D is decreasing and V_{DS} constant)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure H-1.

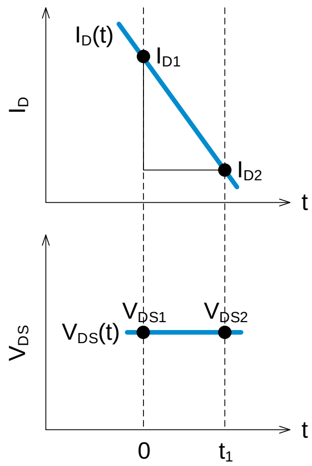


Figure H-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure H-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (H-1).

$$P = f\int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (H-1)$$

where, *f*: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (H-2) and (H-3) from the slopes in Figure H-1.

$$I_D(t) = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t \qquad (H-2)$$

$$V_{DS}(t) = V_{DS1} \qquad (H-3)$$

Substitute (H-2) and (H-3) into (H-1).

$$P = f\int_0^{t_1}\left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t\right)(V_{DS1})dt \qquad (H-4)$$

$$= f\int_0^{t_1}\left(V_{DS1}I_{D1} - \frac{V_{DS1}(I_{D1} - I_{D2})}{t_1}t\right)dt \qquad (H-5)$$

Appendix H (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\,I_{D1}t - \frac{1}{2}\frac{V_{DS1}(I_{D1}-I_{D2})}{t_1}t^2\right]_0^{t_1} \qquad (H-6)$$

$$= f\left[V_{DS1}\,I_{D1}\,t_1 - \frac{1}{2}\frac{V_{DS1}(I_{D1}-I_{D2})}{t_1}t_1^2\right] \qquad (H-7)$$

$$= f\left[V_{DS1}\,I_{D1}\,t_1 - \frac{1}{2}\left(V_{DS1}(I_{D1}-I_{D2})\right)t_1\right] \qquad (H-8)$$

$$= \frac{1}{2}V_{DS1}(I_{D1}+I_{D2})\,t_1\,f \qquad [W] \qquad (H-9)$$

Next, calculate the power loss under the conditions below.

$$I_{D2} \coloneqq 0 \qquad (H-10)$$

Substitute (H-10) into (H-9).

$$P = \frac{1}{2}V_{DS1}\,I_{D1}\,t_1\,f \qquad [W] \qquad (H-11)$$

Appendix I

Calculation of switching loss (when the waveforms of I_D and V_{DS} are decreasing)

From voltage V_{DS} between the drain and source and drain current I_D, calculate the power loss (switching loss) during turn ON and turn OFF using linear approximation. The waveforms to be used for the loss calculation are shown in Figure I-1.

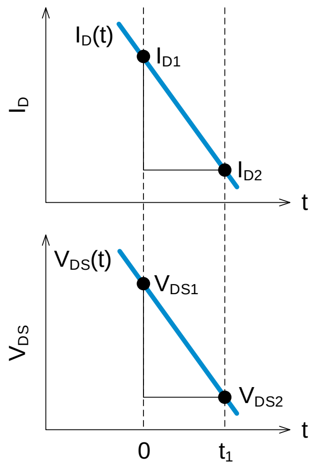


Figure I-1. $I_D(t)$ and $V_{DS}(t)$ in period 0-t_1

Power loss P in period 0-t_1 shown in Figure I-1 can be generally calculated with the integration of the product of the current and the voltage as shown in Equation (I-1).

$$P = f\int_0^{t_1} I_D(t)\, V_{DS}(t)\, dt \qquad (I-1)$$

where, *f*: Switching frequency [Hz]

In addition, $I_D(t)$ and $V_{DS}(t)$ can be represented with Equations (I-2) and (I-3) from the slopes in Figure I-1.

$$I_D(t) = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t \qquad (I-2)$$

$$V_{DS}(t) = V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1}t \qquad (I-3)$$

Substitute (I-2) and (I-3) into (I-1).

$$P = f\int_0^{t_1}\left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}t\right)\left(V_{DS1} - \frac{V_{DS1} - V_{DS2}}{t_1}t\right)dt \qquad (I-4)$$

$$= f\int_0^{t_1}\left(V_{DS1}\, I_{D1} - \frac{I_{D1}(V_{DS1} - V_{DS2}) + V_{DS1}(I_{D1} - I_{D2})}{t_1}t + \frac{(V_{DS1} - V_{DS2})(I_{D1} - I_{D2})}{t_1^2}t^2\right)dt \qquad (I-5)$$

Appendix I (continued)

Perform the integration according to the formula.

$$P = f\left[V_{DS1}\, I_{D1}\, t - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1}\, t^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2}\, t^3\right]_0^{t_1} \qquad (I-6)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\frac{I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})}{t_1}\, t_1^2 + \frac{1}{3}\frac{(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})}{t_1^2}\, t_1^3\right] \qquad (I-7)$$

$$= f\left[V_{DS1}\, I_{D1}\, t_1 - \frac{1}{2}\left(I_{D1}(V_{DS1}-V_{DS2}) + V_{DS1}(I_{D1}-I_{D2})\right)t_1 + \frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2})t_1\right] \qquad (I-8)$$

$$\underline{= \left[\frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad [W]} \qquad (I-9)$$

Next, calculate the power loss under the conditions below.

$$\underline{V_{DS2} \coloneqq 0} \qquad (I-10)$$

Substitute (I-10) into (I-9).

$$P = \left[\frac{1}{3}(V_{DS1}-0)(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}(V_{DS1}-0) - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (I-11)$$

$$= \left[\frac{1}{3}V_{DS1}(I_{D1}-I_{D2}) - \frac{1}{2}I_{D1}\, V_{DS1} - \frac{1}{2}V_{DS1}(I_{D1}-I_{D2}) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (I-12)$$

$$\underline{= \frac{1}{6}V_{DS1}(2\, I_{D1} + I_{D2})t_1\, f \qquad [W]} \qquad (I-13)$$

$$\underline{I_{D2} \coloneqq 0} \qquad (\mathrm{I}-14)$$

Substitute (I-14) into (I-9).

$$P = \left[\frac{1}{3}(V_{DS1}-V_{DS2})(I_{D1}-0) - \frac{1}{2}I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2}V_{DS1}(I_{D1}-0) + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (I-15)$$

$$= \left[\frac{1}{3}(V_{DS1}-V_{DS2})\, I_{D1} - \frac{1}{2}I_{D1}(V_{DS1}-V_{DS2}) - \frac{1}{2}V_{DS1}\, I_{D1} + V_{DS1}\, I_{D1}\right] t_1\, f \qquad (I-16)$$

$$\underline{= \frac{1}{6}(2\, V_{DS1} + V_{DS2})\, I_{D1}\, t_1\, f \qquad [W]} \qquad (I-17)$$

Appendix J

Calculation of power loss during conduction (when I_D is increasing)

From on-resistance R_{ON} of the MOSFET and drain current I_D of the switching waveform, calculate the power loss during conduction (0-t_1) using linear approximation. The waveforms to be used for the loss calculation are shown in Figure J-1.

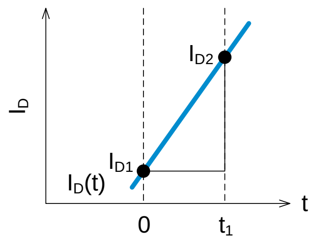


Figure J-1. $I_D(t)$ in period 0-t_1

In Figure J-1, since the MOSFET is energized in period 0-t_1, V_{DS} is the product of on-resistance R_{ON} of the MOSFET and I_D.

Power loss P in period 0-t_1 can be generally calculated with the integration of the product of the resistance and the square of the current as shown in Equation (J-1).

$$P = f\int_0^{t_1} R_{ON}\, I_D(t)^2\, dt \qquad (J-1)$$

where, R_{ON}: On-resistance of MOSFET [Ω]

f: Switching frequency [Hz]

In addition, $I_D(t)$ can be represented with Equation (J-2) from the slope in Figure J-1.

$$I_D(t) = I_{D1} + \frac{I_{D2} - I_{D1}}{t_1} t = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t \qquad (J-2)$$

Substitute (J-2) into (J-1).

$$P = f\int_0^{t_1} R_{ON}\left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}\right)^2 dt \qquad (J-3)$$

$$= f\int_0^{t_1} R_{ON}\left(I_{D1}{}^2 - 2\, I_{D1}\frac{I_{D1} - I_{D2}}{t_1} t + \frac{(I_{D1} - I_{D2})^2}{t_1{}^2} t^2\right) dt \qquad (J-4)$$

Perform the integration according to the formula.

$$P = f\, R_{ON}\left[I_{D1}{}^2 - 2\, I_{D1}\frac{I_{D1} - I_{D2}}{2\, t_1} t^2 + \frac{(I_{D1} - I_{D2})^2}{3\, t_1^2} t^3\right]_0^{t_1} \qquad (J-5)$$

$$= f\, R_{ON}\left(I_{D1}^2\, t_1 - 2\, I_{D1}\frac{I_{D1} - I_{D2}}{2\, t_1}\, t_1^2 + \frac{(I_{D1} - I_{D2})^2}{3\, t_1^2}\, t_1^3\right) \qquad (J-6)$$

$$= f\, R_{ON}\left(I_{D1}^2\, t_1 - I_{D1}\,(I_{D1} - I_{D2})\, t_1 + \frac{(I_{D1} - I_{D2})^2}{3}\, t_1\right) \qquad (J-7)$$

$$= f\, R_{ON}\left(I_{D1}^2 - I_{D1}\,(I_{D1} - I_{D2}) + \frac{(I_{D1} - I_{D2})^2}{3}\right) t_1 \qquad (J-8)$$

Appendix J (continued)

$$P = f\ R_{ON}\left(I_{D1}\,I_{D2} + \frac{{I_{D1}}^2 - 2\ I_{D1}\,I_{D2} + {I_{D2}}^2}{3}\right) t_1 \qquad (J-9)$$

$$= f\ R_{ON}\left(\frac{{I_{D1}}^2 - 2\ I_{D1}\,I_{D2} + {I_{D2}}^2 - 3\ {I_{D1}}^2 + 3\ I_{D1}\,I_{D2} + 3\ {I_{D1}}^2}{3}\right) t_1 \qquad (J-10)$$

$$= \frac{1}{3}\ R_{ON}({I_{D1}}^2 + I_{D1}\,I_{D2} + {I_{D2}}^2)\ t_1\,f \qquad [W] \qquad (J-11)$$

Appendix K

Calculation of power loss during conduction (when I_D is constant)

From on-resistance R_{ON} of the MOSFET and drain current I_D of the switching waveform, calculate the power loss during conduction (0-t_1) using linear approximation. The waveforms to be used for the loss calculation are shown in Figure K-1.

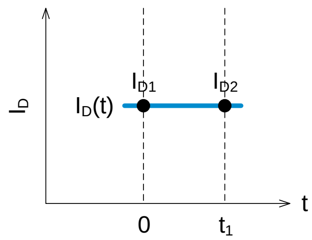


Figure K-1. $I_D(t)$ in period 0-t_1

In Figure K-1, since the MOSFET is energized in period 0-t_1, V_{DS} is the product of on-resistance R_{ON} of the MOSFET and I_D.

Power loss P in period 0-t_1 can be generally calculated with the integration of the product of the resistance and the square of the current as shown in Equation (K-1).

$$P = f\int_0^{t_1} R_{ON}\, I_D(t)^2\, dt \qquad (K-1)$$

where, R_{ON}: On-resistance of MOSFET [Ω]

f: Switching frequency [Hz]

In addition, $I_D(t)$ can be represented with Equation (K-2) from the slope in Figure K-1.

$$I_D(t) = I_{D1} \qquad (K-2)$$

Substitute (K-2) into (K-1).

$$P = \ f\int_0^{t_1} R_{ON}\, I_{D1}^2\, dt \qquad (K-3)$$

Perform the integration according to the formula.

$$P = f\ [R_{ON}\, I_{D1}^2]_0^{t_1} \qquad (K-4)$$

$$= R_{ON}\, I_{D1}^2\, t_1\, f \qquad [W] \qquad (K-5)$$

Appendix L

Calculation of power loss during conduction (when I_D is decreasing)

From on-resistance R_{ON} of the MOSFET and drain current I_D of the switching waveform, calculate the power loss during conduction (0-t_1) using linear approximation. The waveforms to be used for the loss calculation are shown in Figure L-1.

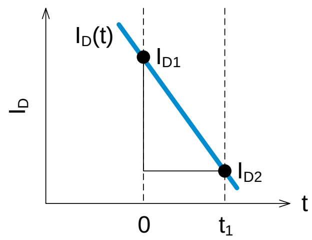


Figure L-1. I_D(t) in period 0-t_1

In Figure L-1, since the MOSFET is energized in period 0-t_1, V_{DS} is the product of on-resistance R_{ON} of the MOSFET and I_D.

Power loss P in period 0-t_1 can be generally calculated with the integration of the product of the resistance and the square of the current as shown in Equation (L-1).

$$P = f\int_0^{t_1} R_{ON}\, I_D(t)^2\, dt \qquad (L-1)$$

where, R_{ON}: On-resistance of MOSFET [Ω]

f: Switching frequency [Hz]

In addition, I_D(t) can be represented with Equation (L-2) from the slope in Figure L-1.

$$I_D(t) = I_{D1} - \frac{I_{D1} - I_{D2}}{t_1} t \qquad (L-2)$$

Substitute (L-2) into (L-1).

$$P = f\int_0^{t_1} R_{ON}\left(I_{D1} - \frac{I_{D1} - I_{D2}}{t_1}\right)^2 dt \qquad (L-3)$$

$$= f\int_0^{t_1} R_{ON}\left({I_{D1}}^2 - 2\, I_{D1}\frac{I_{D1} - I_{D2}}{t_1} t + \frac{(I_{D1} - I_{D2})^2}{{t_1}^2} t^2\right) dt \qquad (L-4)$$

Perform the integration according to the formula.

$$P = f\, R_{ON}\left[{I_{D1}}^2 - 2\, I_{D1}\frac{I_{D1} - I_{D2}}{2\, t_1} t^2 + \frac{(I_{D1} - I_{D2})^2}{3\, t_1^2} t^3\right]_0^{t_1} \qquad (L-5)$$

$$= f\, R_{ON}\left({I_{D1}}^2\, t_1 - 2\, I_{D1}\, \frac{I_{D1} - I_{D2}}{2\, t_1}\, t_1^2 + \frac{(I_{D1} - I_{D2})^2}{3\, t_1^2}\, t_1^3\right) \qquad (L-6)$$

$$= f\, R_{ON}\left({I_{D1}}^2\, t_1 - I_{D1}\, (I_{D1} - I_{D2})\, t_1 + \frac{(I_{D1} - I_{D2})^2}{3}\, t_1\right) \qquad (L-7)$$

$$= f\, R_{ON}\left({I_{D1}}^2 - I_{D1}\, (I_{D1} - I_{D2}) + \frac{(I_{D1} - I_{D2})^2}{3}\right) t_1 \qquad (L-8)$$

Appendix L (continued)

$$P = f\ R_{ON}\left(I_{D1}\,I_{D2} + \frac{{I_{D1}}^2 - 2\,I_{D1}\,I_{D2} + {I_{D2}}^2}{3}\right) t_1 \qquad (L-9)$$

$$= f\ R_{ON}\left(\frac{{I_{D1}}^2 - 2\,I_{D1}\,I_{D2} + {I_{D2}}^2 - 3\,{I_{D1}}^2 + 3\,I_{D1}\,I_{D2} + 3\,{I_{D1}}^2}{3}\right) t_1 \qquad (L-10)$$

$$= \frac{1}{3}\ R_{ON}({I_{D1}}^2 + I_{D1}\,I_{D2} + {I_{D2}}^2)\ t_1\,f \qquad [W] \qquad (L-11)$$

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