Power loss in semiconductor devices

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2017 March 6

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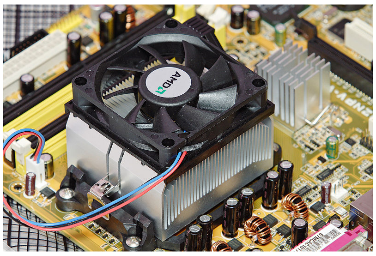
1 Introduction

Why is this important?

Almost all power semiconductor devices dissipate enough power that the devices must be cooled for safe operation.



Old-fashioned devices often needed heatsinks to cool them, perhaps a fan too. Modern devices are more efficient and the printed circuit board (PCB) may be enough.

[Image from Wikipedia.] The design of the system needs two steps:

1. Calculation of power loss in devices (these notes)
2. Arrangements to remove excess heat (next notes)

You should be able to calculate the switching and conduction losses in diodes (and diode-like devices) and MOSFETs. The formulae are provided in the exam but you need to understand how to use them.

In low-power electronics, such as dealing with opamps, you can often assume that components are ideal (perfect behaviour). Unfortunately this is never true with power electronics.

Introduction

The characteristics of a perfect switch were set out near the start of this course:

1. Infinite resistance (zero current) when **off**
2. Zero resistance (zero voltage drop) when **on**
3. Instantaneous **switching**
4. Can carry infinite current and resist infinite voltage

No real switch fulfils any of these characteristics exactly:

1. They leak a little current when **off**, although this is usually small enough to neglect.
2. They have a nonzero voltage drop when **on**, which means that they dissipate power.
3. They take a finite time to **switch on and off**, which also causes power dissipation.
4. They are damaged if the current or blocking voltage exceed the ratings of the device (so don't!)

Two main sources of power loss

These notes explore the two main sources of power loss in semiconductor switches:

- **conduction losses**, P_{cond} – caused by the nonzero voltage drop when **on** (conducting)
- **switching losses**, P_{sw} – caused by the finite time to **switch on and off**

We shall look at two classes of device, which require different calculations for P_{cond} and P_{sw}:

- **diodes** (including SCRs and TRIACs) – have a (roughly) constant voltage drop when conducting, and pass a *reverse recovery charge* when they switch off

- **FETs** – behave like resistors controlled by the gate voltage

Bipolar junction transistors (BJTs) have similar power losses to diodes.

These notes cover only the average values of power dissipation in a steady state. The transient behaviour can also be calculated but is more advanced. These are not the only processes that dissipate energy. For example, the gate of a MOSFET behaves like a capacitor and must be charged and discharged to turn the device on and off, which consumes energy. Turning an SCR on with a firing pulse also consumes energy. In most cases these are smaller than the losses calculated in these notes.

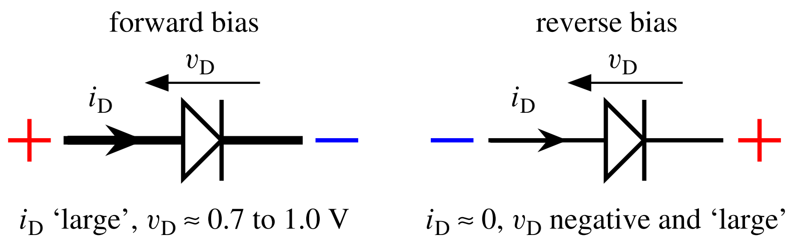
2 Diodes, SRCs and TRIACs

2.1 Diodes

Power loss in diodes

The possible sources of loss are:

1. Leakage when reverse biassed – negligible
2. **Conduction loss** when forward biassed – significant.
3. Switching loss when turning on – usually negligible because diodes turn on very quickly.
4. **Switching loss when turning off** – significant because standard diodes turn off more slowly than they turn on.



Different types of diode are available to reduce particular losses, as was mentioned in the lectures on diodes. For example, Schottky diodes have a lower forward voltage drop than standard diodes and switch off more quickly, with negligible reverse recovery charge (Q_{RR}, later). However, their reverse leakage current is higher and reverse voltage rating is lower.

Conduction loss in a diode

The general expression for average power loss over a period T is

$$P_{ave} = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T v(t)\,i(t)\,dt\,. \qquad (1)$$

The voltage drop across a diode is approximately constant when it is forward biassed and conducting, so $v(t) \approx V_F$. This simplifies the integral for the conduction loss.

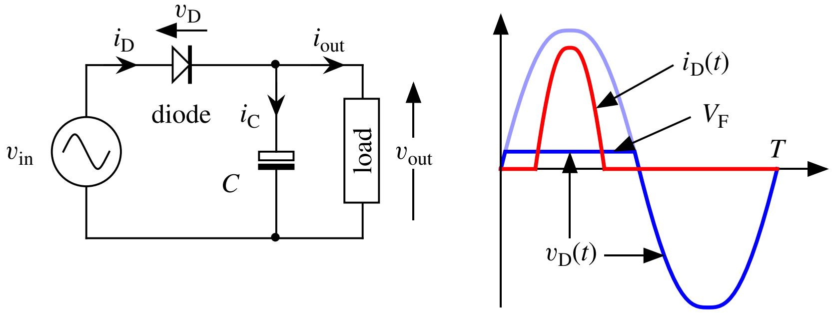
$$P_{\text{cond}} = \frac{1}{T}\int V_F\, i(t)\, dt = V_F\left[\frac{1}{T}\int i(t)\, dt\right] = V_F\, I_{\text{ave}}. \tag{2}$$

This contains the 'ordinary' average, not the RMS value.

The integral for I_{ave} must be done over the part of the cycle when the diode is conducting. We assume that $i(t) = 0$ for the rest of the time.

Many loads are inductive, in which case current continues to flow even when the supply voltage drops to zero. See later.

Conduction loss in a half-wave rectifier

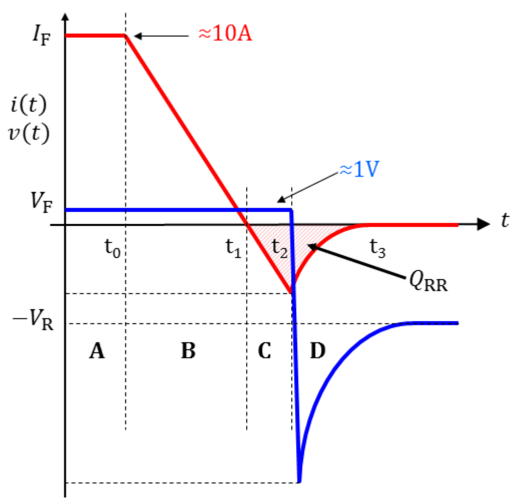


The two half-cycles make different contributions to the average conduction power loss P_{cond} and average current I_{ave}.

- For the first (positive) half-cycle, the diode is forward biassed so $v_D(t) \approx V_F$ and a large current $i_D(t)$ flows.
- For the second (negative) half-cycle, the diode is reverse biassed so $i(t) = 0$. This half-cycle makes no contribution.

Turnoff losses in a diode

The behaviour of a diode at turnoff was shown earlier.



Charge Q_{RR} flows in the **reverse** direction when the diode turns off. The reverse voltage is $-V_R$ so energy loss $E_{sw} = Q_{RR}V_R$.

Total power loss in a diode

An energy E_{sw} is lost every time the diode switches off. If this happens at a switching frequency f_{sw}, the average switching power loss is

$$P_{sw} = E_{sw}f_{sw} = Q_{RR}V_Rf_{sw}\,. \tag{3}$$

This expression is provided on the exam data sheet.

The total power loss is the sum of the conduction and switching losses

$$P_{tot} = P_{cond} + P_{sw} = V_FI_{ave} + Q_{RR}V_Rf_{sw}\,. \tag{4}$$

Reminder:

- V_F – voltage across forward-biassed diode (around 0.7 to 1.0 V)
- I_{ave} – average forward current through diode (depends on circuit, ampères)
- Q_{RR} – reverse recovery charge (from data sheet, coulombs)
- V_R – reverse blocking voltage across diode when it switches off (depends on circuit, volts)
- f_{sw} – switching frequency (depends on system, Hz)

Diode example (1)

Calculate the dissipation for the following diode in a power supply:

- forward current $i_D = I_F = 10\,\mathrm{A}$ when conducting
- forward voltage $v_D = V_F = 1.1\,\mathrm{V}$ when conducting
- reverse voltage $v_D = -V_R = -50\,\mathrm{V}$ when blocking
- duty cycle $D = 50\%$
- switching frequency $f_{sw} = 31.5\,\mathrm{kHz}$
- reverse recovery charge $Q_{RR} = 2.5\,\mu\mathrm{C}$

Conduction loss:

$$P_{cond} = V_FI_{ave} = V_FDI_F = (1.1\,\mathrm{V}) \times 0.5 \times (10\,\mathrm{A}) = 5.5\,\mathrm{W}. \tag{5}$$

Switching loss:

$$P_{sw} = Q_{RR}V_Rf_{sw} = (2.5\,\mu\mathrm{C}) \times (50\,\mathrm{V}) \times (31.5\,\mathrm{kHz}) = 3.9\,\mathrm{W}. \tag{6}$$

The total is 9.4 W. (This is high for a diode and would probably need a heatsink.)

Both contributions to the dissipation could be reduced with a Schottky diode provided that its reverse characteristics were acceptable. This is particularly important in modern switching circuits, which operate at MHz rather than kHz.

Diode example (2)

The conduction loss is larger. What would change this?

1. Suppose that the switching frequency is raised from 31.5 kHz to 100 kHz. This raises the switching loss to 12.5 W because $P_{\mathrm{sw}} \propto f_{\mathrm{sw}}$. The conduction loss are unchanged. **High frequency increases switching losses.**
2. Suppose instead that the duty cycle is reduced from 50% to 25%. This halves the average current and the conduction loss falls to 2.8 W because $P_{\mathrm{cond}} \propto I_{\mathrm{ave}}$. The switching loss is now greater.

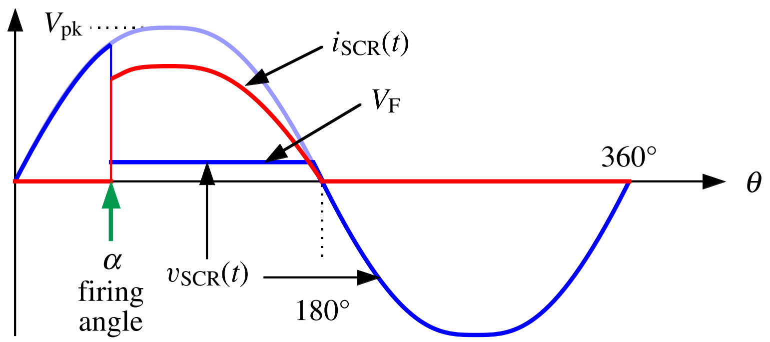
It is useful to know which loss dominates because you may need to reduce the overall loss.

- If **conduction** loss dominates, find a diode with lower forward voltage drop V_{F}.
- If **switching** loss dominates, look for a diode with lower reverse recovery charge Q_{RR}.

A Schottky diode offers both improvements but with less good reverse characteristics.

2.2 SCRs and TRIACs

Power loss in an SCR with a resistive load



SCRs are diodes that do not begin to conduct until a firing pulse at angle α through the positive half cycle. Typically $V_{\mathrm{F}} \approx 2\,\mathrm{V}$.

Current flows only between α and 180° so its average is

$$I_{\mathrm{ave}} = \frac{1}{360^\circ} \int_{\alpha}^{180^\circ} i_{\mathrm{SCR}}(\theta)\,\mathrm{d}\theta \tag{7}$$

Average current is proportional to average load voltage:

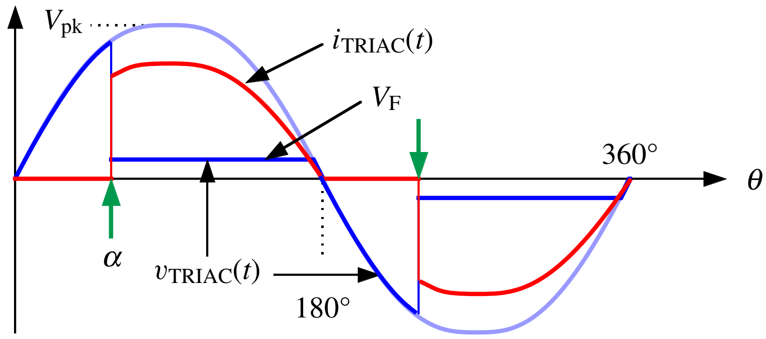
$$I_{\mathrm{ave}} = \frac{V_{\mathrm{ave}}}{R_{\mathrm{load}}} = \frac{1}{R_{\mathrm{load}}}\left[\frac{V_{\mathrm{pk}}}{\pi}\frac{1+\cos\alpha}{2}\right]. \tag{8}$$

The power dissipated in the **load** depends on I_{rms}, not I_{ave}.

Switching losses usually low (mains, 50 or 60 Hz).

The average voltage across a resistive load was calculated in the lectures on SRCs. So was the RMS voltage, which is needed for the power dissipated in the load.

Power loss in a TRIAC with a resistive load



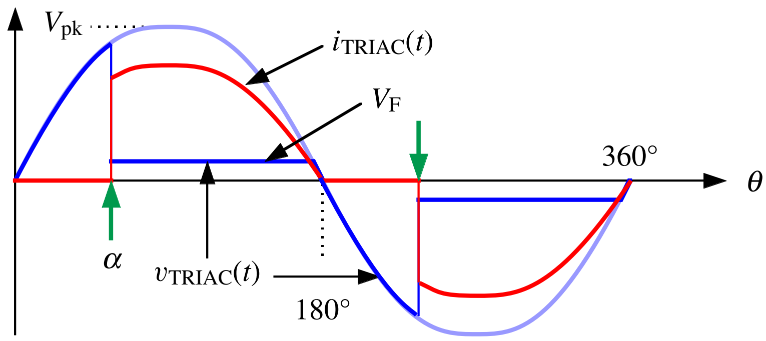
These are like SRCs but conduct in both half-cycles, which are symmetric so the average current can be calculated from the first,

$$I_{ave} = \frac{1}{180^{\circ}} \int_{\alpha}^{180^{\circ}} i_{SCR}(\theta)\,\mathrm{d}\theta = \frac{1}{R_{load}} \left[\frac{2V_{pk}}{\pi} \frac{1 + \cos\alpha}{2} \right]. \tag{9}$$

This has 180° in the denominator instead of 360°.

This is the same as two SCRs in antiparallel, firing at the same angle.

TRIAC with resistive load example (1)



A 3 kW mains heater is controlled by a TRIAC with $V_F = 2.0$ V.

1. What is the power in the heater with a delay angle $\alpha = 60^{\circ}$?
2. How much power is dissipated in the TRIAC under these conditions?
3. What is the maximum power dissipation in the TRIAC?

Assume that the heater is resistive. 'Mains' means 230 V RMS at 50 Hz in Europe, peak voltage $V_{pk} = \sqrt{2} \times 230 = 325.3$ V.

TRIAC with resistive load example (2)

Find the resistance of the heater from $P_{\text{ave}} = R\,I_{\text{rms}}^2 = V_{\text{rms}}^2/R$. **RMS voltage and current give dissipation in a resistor.**

$$R = \frac{V_{\text{rms}}^2}{P_{\text{ave}}} = \frac{(230\,\text{V})^2}{3000\,\text{W}} = 17.6\,\Omega. \tag{10}$$

The **RMS** voltage controlled by a TRIAC is given by

$$V_{\text{rms}}^2(\alpha) = \frac{V_{\text{pk}}^2}{2}\left[\frac{2\pi - 2\alpha + \sin(2\alpha)}{2\pi}\right]. \tag{11}$$

Write as power instead using $P_{\text{ave}} = V_{\text{rms}}^2/R$ and $V_{\text{rms}} = V_{\text{pk}}/\sqrt{2}$:

$$P_{\text{ave}}(\alpha) = P_{\text{full}}\left[\frac{2\pi - 2\alpha + \sin(2\alpha)}{2\pi}\right]. \tag{12}$$

Check: if $\alpha = 0$, $P_{\text{ave}} = P_{\text{full}}$ (full power, 3 kW); if $\alpha = \pi$, $P_{\text{ave}} = 0$.

Putting $\alpha = 60^\circ = (\pi/3)$ rad gives $P_{\text{ave}} = 0.80\,P_{\text{full}} = 2.4\,\text{kW}$.

Alternatively, $V_{\text{rms}} = 206.3\,\text{V}$ and $I_{\text{rms}} = 11.7\,\text{A}$.

I have ignored the voltage dropped across the TRIAC in the relation between voltage and power to find the resistance of the heater. The expression for $V_{\text{rms}}^2(\alpha)$ was derived in the lectures on SRCs and TRIACs. Remember that $alpha$ must be in radians for these expressions.

TRIAC with resistive load example (3)

The conduction power loss in the TRIAC is given by $P_{\text{cond}} = V_{\text{F}} I_{\text{ave}}$ with the **average** current, not RMS. The average voltage is

$$V_{\text{ave}} = \frac{2V_{\text{pk}}}{\pi}\left[\frac{1+\cos\alpha}{2}\right] = (207.1\,\text{V})\left[\frac{1+\cos\alpha}{2}\right]. \tag{13}$$

Putting $\alpha = 60^\circ$ gives $V_{\text{ave}} = 155.3\,\text{V}$.

Dividing by $R = 17.6\,\Omega$ gives $I_{\text{ave}} = 8.81\,\text{A}$ (lower than RMS).

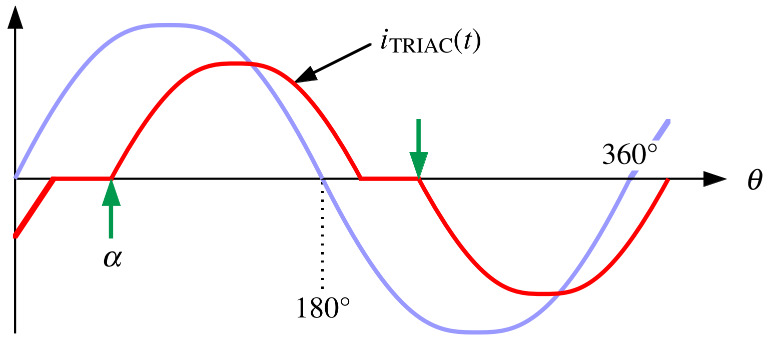
Multiplying by $V_{\text{F}} = 2.0\,\text{V}$ gives $P_{\text{cond}} = 17.6\,\text{W}$. This is the average power dissipated in the TRIAC.

Maximum power dissipation occurs at maximum current and maximum power in the load. This means $\alpha = 0$, load switched on continuously. Then $V_{\text{ave}} = 207.1\,\text{V}$, $I_{\text{ave}} = 11.7\,\text{A}$ and $P_{\text{cond}} = 23.5\,\text{W}$.

This is much smaller than the 3 kW power in the load but is high for a semiconductor device so cooling is required.

The average values are for a full-wave rectified wave, not the most straightforward average because this would be zero. Both the average current and the forward voltage change sign in alternate half-cycles so the power dissipation is always postive.

Power loss in a TRIAC with an inductive load



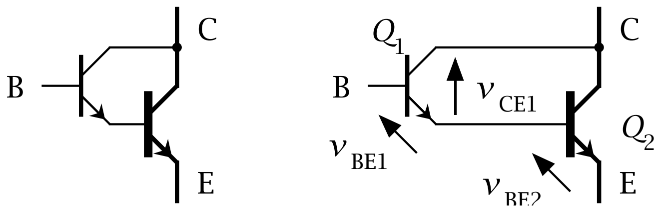
Many loads, such as motors, are inductive and the waveforms are more complicated. Current continues to flow after v_{supply} passes through zero (*very* rough sketch). Losses in the TRIAC (or SCR) can be calculated in a similar way, but **not in this course**.

The waveforms in a switching supply are quite different: later.

The majority of loads switched by power electronic devices are inductive (or reactive more generally) and calculations of power loss should take this into account. However, it is too complicated for a general course that includes non-electrical engineering students. The sketch of the current is *very* rough.

2.3 Bipolar junction transistors

Power loss in a bipolar junction transistors (BJT)



A BJT behaves in a similar way to a diode. The voltage across a BJT when it is turned fully on (saturated) is roughly constant at $V_{\mathrm{CE,sat}}$.

- Single transistor: $V_{\mathrm{CE,sat}} \approx 0.2\,\mathrm{V}$
- Darlington pair: $V_{\mathrm{CE,sat}} \approx 1.0\,\mathrm{V}$

The conduction loss can be calculated in the same way as a diode.

Switch-off losses are calculated in the same way as MOSFETs later but BJTs are slower so the losses are larger.

BJTs are slower because a lot of stored charge builds up inside the transistor when it is saturated and this must be removed before the transistor can switch off. This is a detail for electronics students.

3 MOSFETs

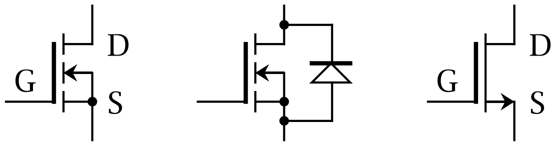
Power loss in a MOSFET

Recall how a MOSFET works as a switch:

- The channel between source and drain is a resistor controlled by the voltage on the gate
- The resistance falls to $R_{\mathrm{DS,on}}$ when the MOSFET is on.

There are two main losses as usual:

- **conduction losses** P_{cond} caused by the resistance $R_{\mathrm{DS,on}}$
- **switching losses** when the MOSFET switches on and off



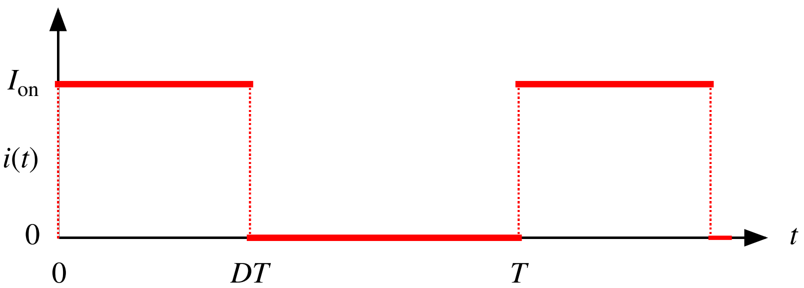
The channel is a resistance so the conduction loss is

$$P_{\mathrm{cond}} = R_{\mathrm{DS,on}} I^2_{\mathrm{D,rms}}. \tag{14}$$

Other sources of loss include the capacitances that are charged and discharged when the MOSFET is switched on and off, including the input capacitance due to the gate.

3.1 MOSFETs with resistive loads

Average currents for PWM with a resistive load



Current constant at I_{on} when on, zero when off (resistive load).

Average values:

$$I_{\mathrm{ave}} = DI_{\mathrm{on}} \tag{15}$$
$$I^2_{\mathrm{rms}} = DI^2_{\mathrm{on}} \tag{16}$$
$$I_{\mathrm{rms}} = \sqrt{D}\, I_{\mathrm{on}} \tag{17}$$

Formal proof of simple average:

$$I_{\text{ave}} = \frac{1}{T}\int_0^T i(t)\,\mathrm{d}t = \frac{1}{T}\left[\int_0^{DT} I_{\text{on}}\,\mathrm{d}t + \int_{DT}^{T} 0\,\mathrm{d}t\right] = DI_{\text{on}}\,. \tag{18}$$

Explain this more physically from the area under the plot or the definition of duty cycle. Similarly for RMS value:

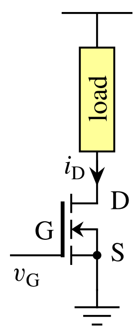
$$I_{\text{rms}}^2 = \frac{1}{T}\int_0^T [i(t)]^2\,\mathrm{d}t = \frac{1}{T}\left[\int_0^{DT} I_{\text{on}}^2\,\mathrm{d}t + \int_{DT}^{T} 0\,\mathrm{d}t\right] = DI_{\text{on}}^2\,. \tag{19}$$

More physically, $P = DP_{\text{on}}$ and $P = R_{\text{load}}I_{\text{rms}}^2$ so $I_{\text{rms}} \propto \sqrt{D}$.

Don't forget the square root.

This assumes pulse width modulation (PWM) with a resistive load, which gives a constant current from a constant supply voltage. Not all loads are like this!

MOSFET with resistive load example (1)



A MOSFET with $R_{\text{DS,on}} = 0.1\,\Omega$ is used as a low-side switch for a $5.0\,\Omega$ load from a 12 V supply.

1. Calculate the current flowing and power dissipated in the load and MOSFET when the MOSFET is on.
2. Find the average and RMS currents and powers dissipated with PWM and $D = 0.5$.
3. Find D to dissipate 10 W in the load.

When the MOSFET is on, $I_{\text{on}} \approx (12\,\text{V})/(5.0\,\Omega) = 2.4\,\text{A}$.

The power in the load can be found from $P_{\text{load,on}} = (12\,\text{V}) \times (2.4\,\text{A}) = 28.8\,\text{W}$ or $P_{\text{load,on}} = R_{\text{load}}I_{\text{on}}^2 = (5\,\Omega) \times (2.4\,\text{A})^2 = 28.8\,\text{W}$.

The voltage across the MOSFET is $V_{\text{DS,on}} = R_{\text{DS,on}}I_{\text{on}} = (0.1\,\Omega) \times (2.4\,\text{A}) = 0.24\,\text{V}$. The power dissipated is $P_{\text{cond,on}} = (2.4\,\text{A}) \times (0.24\,\text{V}) = 0.6\,\text{W}$. This is much smaller than $P_{\text{load,on}}$, as it should be.

I have cheated a little! The current should really be calculated with the total resistance of the load and MOSFET in series, $5.0 + 0.1 = 5.1\,\Omega$. In practice we usually assume that the resistance of the switch is negligible compared with the load. Get a better switch if this is not true.

MOSFET with resistive load example (2)

Now for PWM with $D = 0.5$. The current flows for only half the time so $I_{\text{ave}} = D\,I_{\text{on}} = 0.5 \times 2.4 = 1.2\,\text{A}$.

In the same way, the average powers are halved to $P_{\text{load}} = 14.4\,\text{W}$ and $P_{\text{cond}} = 0.3\,\text{W}$. This includes only the conduction loss for the MOSFET.

You cannot find the RMS value so simply because it is not a simple average: it involves squaring and square-rooting.

The RMS current can be found from $P_{\text{ave}} = R\,I_{\text{rms}}^2$. Using the load,

$$I_{\text{rms}} = \sqrt{\frac{P_{\text{load}}}{R_{\text{load}}}} = \sqrt{\frac{14.4\,\text{W}}{5\,\Omega}} = \sqrt{2.88} = 1.7\,\text{A}. \tag{20}$$

Alternatively, $I_{\text{rms}} = \sqrt{D}\,I_{\text{on}} = \sqrt{0.5} \times 2.4\,\text{A} = 1.7\,\text{A}$.

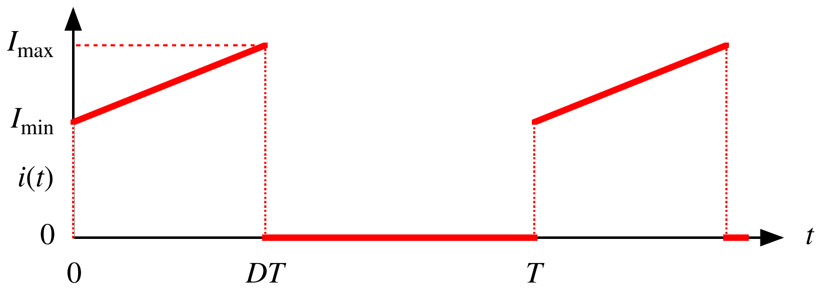
The RMS current is larger than the average current, as it should be.

To dissipate 10.0 W in the load, $D = 10.0/28.8 = 0.35$.

The MOSFET also has a switching loss, to be calculated shortly.

3.2 MOSFETs with inductive loads

Average currents for PWM with an inductive load



A more typical current looks like this (SMPS laboratory).

$$I_{\text{ave}} = D\frac{I_{\text{min}} + I_{\text{max}}}{2} \tag{21}$$

$$I_{\text{rms}}^2 = D\frac{I_{\text{min}}^2 + I_{\text{min}}I_{\text{max}} + I_{\text{max}}^2}{3} \tag{22}$$

Algebraic derivation in notes. See numerical example shortly.

Here is the calculation for the results on the slide. As usual we need the integrals

$$I_{\text{ave}} = \frac{1}{T}\int_0^T i(t)\,\text{d}t\,. \tag{23}$$

and

$$I_{\text{rms}}^2 = \frac{1}{T}\int_0^T [i(t)]^2\text{d}t\,. \tag{24}$$

First we need an expression for $i(t)$. The plots are straight lines so in general $i = mt + c$ where m is the slope and c is the intercept. The intercept is clearly $c = I_{\mathrm{min}}$ and the slope is given by

$$m = \frac{\Delta i}{\Delta t} = \frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{DT}. \tag{25}$$

This can also be written $mDT = I_{\mathrm{max}} - I_{\mathrm{min}}$, which comes in handy later. It is neater to keep $i(t) = mt + I_{\mathrm{min}}$ and substitute the expression for m at the end, or the expressions get very cumbersome. The integrals go from $t = 0$ to DT because the current flows only during this interval but the denominator is the full period, T.

The average is

$$\begin{aligned}
I_{\mathrm{ave}} &= \frac{1}{T}\int_0^{DT} (mt + I_{\mathrm{min}})\mathrm{d}t && (26)\\
&= \frac{1}{T}\left[\frac{mt^2}{2} + I_{\mathrm{min}}t\right]_0^{DT} && (27)\\
&= \frac{1}{T}\left[\frac{mD^2T^2}{2} + I_{\mathrm{min}}DT\right] && (28)\\
&= \frac{mD^2T}{2} + DI_{\mathrm{min}} && (29)\\
&= D\frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{2} + DI_{\mathrm{min}} && (30)\\
&= D\frac{I_{\mathrm{max}} + I_{\mathrm{min}}}{2}. && (31)
\end{aligned}$$

This is not a big surprise. The average current during the duty cycle is halfway between the maximum and minimum values and the duty cycle is a fraction D of the period.

Now for the RMS value. This is more complicated but the integrals are still elementary.

$$\begin{aligned}
I_{\mathrm{rms}}^2 &= \frac{1}{T}\int_0^{DT} (mt + I_{\mathrm{min}})^2\mathrm{d}t && (32)\\
&= \frac{1}{T}\int_0^{DT} (m^2t^2 + 2I_{\mathrm{min}}mt + I_{\mathrm{min}}^2)\mathrm{d}t && (33)\\
&= \frac{1}{T}\left[\frac{m^2t^3}{3} + 2I_{\mathrm{min}}\frac{mt^2}{2} + I_{\mathrm{min}}^2 t\right]_0^{DT} && (34)\\
&= \frac{1}{T}\left[\frac{m^2D^3T^3}{3} + I_{\mathrm{min}}mD^2T^2 + I_{\mathrm{min}}^2DT\right] && (35)\\
&= D\left(\frac{m^2D^2T^2}{3} + I_{\mathrm{min}}mDT + I_{\mathrm{min}}^2\right). && (36)
\end{aligned}$$

I have taken a factor of D out because it leaves the combination $mDT = I_{\mathrm{max}} - I_{\mathrm{min}}$.

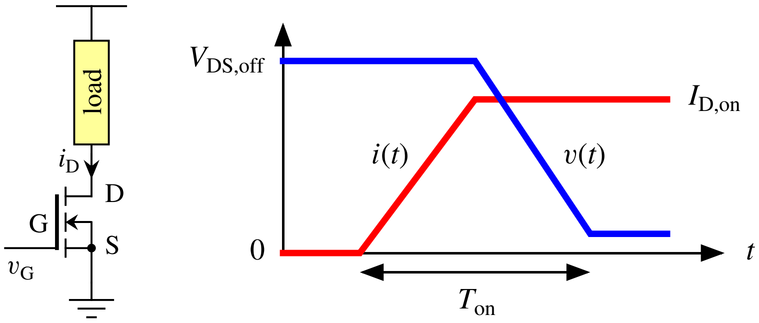
$$\begin{aligned}
I_{\mathrm{rms}}^2 &= D\left[\frac{(I_{\mathrm{max}} - I_{\mathrm{min}})^2}{3} + I_{\mathrm{min}}(I_{\mathrm{max}} - I_{\mathrm{min}}) + I_{\mathrm{min}}^2\right] && (37)\\
&= \frac{D}{3}[(I_{\mathrm{max}} - I_{\mathrm{min}})^2 + 3I_{\mathrm{min}}(I_{\mathrm{max}} - I_{\mathrm{min}}) + 3I_{\mathrm{min}}^2] && (38)\\
&= \frac{D}{3}(I_{\mathrm{max}}^2 - 2I_{\mathrm{max}}I_{\mathrm{min}} + I_{\mathrm{min}}^2 + 3I_{\mathrm{min}}I_{\mathrm{max}} - 3I_{\mathrm{min}}^2 + 3I_{\mathrm{min}}^2) && (39)\\
&= D\frac{I_{\mathrm{max}}^2 + I_{\mathrm{max}}I_{\mathrm{min}} + I_{\mathrm{min}}^2}{3} && (40)
\end{aligned}$$

This is the required result. It is a good idea to check it. Suppose that the current is constant and the graph is a horizontal straight line. In this case $I_{\max} = I_{\min} = I_{\mathrm{DC}}$ and the RMS value becomes $I_{\mathrm{rms}}^2 = DI_{\mathrm{DC}}^2$.

Switching-on energy loss in a MOSFET

When a MOSFET switches on:

1. the drain current rises from zero to $I_{\mathrm{D,on}}$
2. the drain voltage falls from $V_{\mathrm{DS,off}}$ to nearly zero



This happens in a time T_{on} and the energy dissipated is roughly

$$E_{\mathrm{sw,on}} = \frac{I_{\mathrm{D,on}} V_{\mathrm{DS,off}} T_{\mathrm{on}}}{2} \tag{41}$$

Total power loss in a MOSFET

The energy $E_{\mathrm{sw,on}} = I_{\mathrm{D,on}} V_{\mathrm{DS,off}} T_{\mathrm{on}}/2$ is lost every time the MOSFET switches on. If this happens at a switching frequency f_{sw}, the average switching-on power loss is

$$P_{\mathrm{sw,on}} = E_{\mathrm{sw,on}} f_{\mathrm{sw}} = \frac{I_{\mathrm{D,on}} V_{\mathrm{DS,off}} T_{\mathrm{on}} f_{\mathrm{sw}}}{2}. \tag{42}$$

A similar loss occurs when the MOSFET switches off. Usually the voltage is the same but the current is often different, $I_{\mathrm{DS,on}}$. The switching time T_{off} may be different too, although often it is the same as T_{on}.

The total switching loss is

$$P_{\mathrm{sw}} = \frac{f_{\mathrm{sw}} V_{\mathrm{DS,off}} (I_{\mathrm{D,on}} T_{\mathrm{on}} + I_{\mathrm{D,off}} T_{\mathrm{off}})}{2}. \tag{43}$$

This expression is provided on the exam data sheet.

Total power loss in a MOSFET

The total power loss is

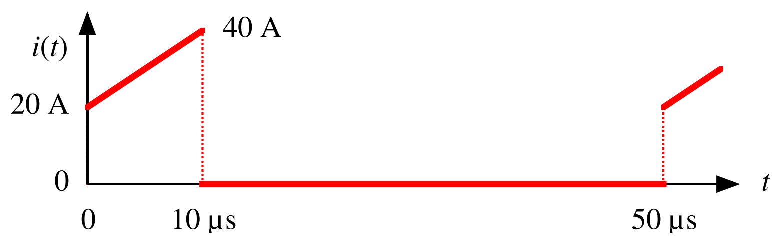
$$P_{\text{tot}} = R_{\text{DS,on}} I_{\text{D,rms}}^2 + \frac{f_{\text{sw}} V_{\text{DS,off}} (I_{\text{D,on}} T_{\text{on}} + I_{\text{D,off}} T_{\text{off}})}{2}. \tag{44}$$

Reminder:

- $R_{\text{DS,on}}$ – 'on' resistance of MOSFET (data sheet, below $1\,\Omega$)
- T_{on} – turn-on time of MOSFET (data sheet, 10s of ns)
- T_{off} – turn-off time of MOSFET (data sheet, 10s of ns)
- $V_{\text{DS,off}}$ – voltage across MOSFET when switched off (V)
- $I_{\text{D,on}}$ – drain current of MOSFET at switch-on (A)
- $I_{\text{D,off}}$ – drain current of MOSFET at switch-off (A)
- $I_{\text{D,rms}}$ – RMS drain current of MOSFET (A)
- f_{sw} – switching frequency (Hz)

3.3 MOSFET in a SMPS

MOSFET SMPS example



Calculate the losses in the MOSFET used to switch this SMPS current waveform. Other parameters:

- Supply voltage $V_{\text{supply}} = 42\,\text{V}$
- 'On' resistance of MOSFET $R_{\text{DS,on}} = 7\,\text{m}\Omega$
- Turn-on time of MOSFET $T_{\text{on}} = 10\,\text{ns}$
- Turn-off time of MOSFET $T_{\text{off}} = 30\,\text{ns}$

Start with the switching losses, which are easier to calculate.

$$\begin{aligned} P_{\text{sw}} &= \frac{f_{\text{sw}} V_{\text{DS,off}} (I_{\text{D,on}} T_{\text{on}} + I_{\text{D,off}} T_{\text{off}})}{2} \\ &= \frac{(20\,\text{kHz})(42\,\text{V})[(20\,\text{A})(10\,\text{ns}) + (40\,\text{A})(30\,\text{ns})]}{2} \\ &= \frac{(8.4 \times 10^5)[(200 + 1200) \times 10^{-9}]}{2} = 0.6\,\text{W}. \end{aligned} \tag{45}$$

The conduction loss needs the RMS current, which must be calculated.

The current $i(t)$ is a straight line so write $i = mt + c$. The intercept c is clearly $I_{\text{on}} = 20\,\text{A}$. Substitute $I_{\text{off}} = 40\,\text{A}$ at $t = 10\,\mu\text{s}$:

$$40 = 10m + 20 \quad \text{so} \quad 20 = 10m \quad \text{and} \quad m = 2.0\,. \tag{46}$$

Thus $i = 2\,t + 20$ (units of A and µs).

No voltage is dropped across the load when no current flows through it. This means that the voltage across the MOSFET when it is switched off is the same as the supply voltage, so $V_{\text{DS,off}} = V_{\text{supply}}$.

The switching frequency is the inverse of the period of PWM, which is 50 µs from the plot if $i(t)$, hence 20 kHz.

Watch the power of 10 for nanoseconds, ns: it is 10^{-9}.

The loss is much larger when switching off than switching on. This is partly because of the higher current, which is common, but also because $T_{\text{off}} \gg T_{\text{on}}$, which is unusual.

MOSFET SMPS example RMS current

Integral for RMS current:

$$\begin{aligned}
I_{\text{rms}}^2 &= \frac{1}{T}\int_0^T [i(t)]^2 \mathrm{d}t \\
&= \frac{1}{50}\int_0^{10} (2\,t + 20)^2 \mathrm{d}t \\
&= \frac{1}{50}\int_0^{10} (4\,t^2 + 80\,t + 400)\mathrm{d}t \\
&= \frac{1}{50}\left[\frac{4\,t^3}{3} + \frac{80\,t^2}{2} + 400\,t\right]_0^{10} \\
&= \frac{1}{50}\left[\frac{4000}{3} + \frac{8000}{2} + 4000\right] \\
&= \frac{1}{50}\frac{28000}{3} = \frac{560}{3} = 186.7\,\text{A}^2
\end{aligned} \tag{47}$$

so $I_{\text{rms}} = 13.7\,\text{A}$. (Check against $I_{\text{ave}} = 6.0\,\text{A}$.)

We don't need the average current for this calculation but it's a useful check because it should be smaller than the RMS current, but with a similar magnitude. The average current during the duty cycle is 30 A (the average of $I_{\text{on}} = 20\,\text{A}$ and $I_{\text{off}} = 40\,\text{A}$). The duty cycle is 0.2 so $I_{\text{ave}} = 0.2 \times (30\,\text{A}) = 6\,\text{A}$. This looks consistent with I_{rms} because the current is 'spikey' so we would expect the RMS value to be considerably larger than the simple average.

MOSFET SMPS example power loss

The average conduction loss is

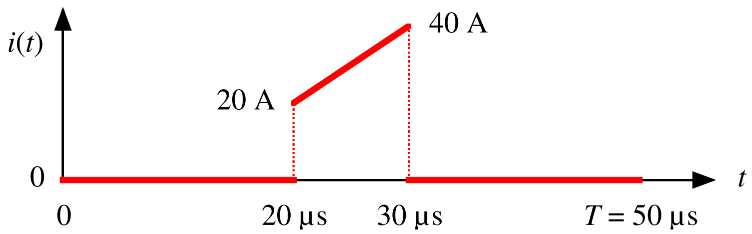
$$P_{\text{cond}} = R_{\text{DS,on}} I_{\text{D,rms}}^2 = (7\,\text{m}\Omega) \times (186.7\,\text{A}^2) = 1.3\,\text{W}. \tag{48}$$

This is about double the switching loss of $P_{\text{sw}} = 0.6\,\text{W}$ and the total is $P_{\text{tot}} = 1.9\,\text{W}$.

This would probably need a heatsink. Buy a MOSFET with a lower 'on' resistance to reduce this loss.

3.4 Slightly different SMPS waveform

Suppose instead that the pulse of current in each cycle was from 20 µs to 30 µs instead of from 0 to 10 µs. This does not affect the final result because the origin of time can be chosen anywhere. It makes the calculation a bit more complicated, though, and many students have problems deriving $i(t)$ so here is the working.



The current $i(t)$ is a straight line so write $i = mt + c$. We know the current at two times:

$$\begin{aligned} 20 &= 20\,m + c \\ 40 &= 30\,m + c \end{aligned} \tag{49}$$

Subtracting these gives

$$20 = 10\,m \tag{50}$$

so $m = 2$ as before. Substitute this into the first equation:

$$20 = 20 \times 2 + c = 40 + c \tag{51}$$

so $c = -20$ and $i(t) = 2\,t - 20$ (units of A and µs).

Now we can do the integral for RMS current as before:

$$\begin{aligned} I^2_{\text{rms}} &= \frac{1}{T}\int_0^T [i(t)]^2 \mathrm{d}t \\ &= \frac{1}{50}\int_{20}^{30} (2\,t - 20)^2 \mathrm{d}t \\ &= \frac{1}{50}\int_{20}^{30} (4\,t^2 - 80\,t + 400)\mathrm{d}t \\ &= \frac{1}{50}\left[\frac{4\,t^3}{3} - \frac{80\,t^2}{2} + 400\,t\right]_{20}^{30} \\ &= \frac{1}{50}\left[\frac{108000}{3} - \frac{72000}{2} + 12000 - \frac{32000}{3} + \frac{32000}{2} - 8000\right] \\ &= \frac{1}{50}\frac{28000}{3} = \frac{560}{3} = 186.7\,\mathrm{A}^2 \end{aligned} \tag{52}$$

This is the same as before.

4 Summary

Summary

1. The major losses in power semiconductor devices are **conduction** and **switching**.
2. Diodes have a constant voltage drop and $P_{\text{cond}} = V_{\text{F}} I_{\text{ave}}$ with the **ordinary** average current.
3. For MOSFETs the channel is a resistor so $P_{\text{cond}} = R_{\text{DS,on}} I_{\text{D,rms}}^2$ with the **RMS** current.
4. Switching losses are proportional to switching frequency and blocking voltage; formulae provided in exam.

These losses are dissipated as heat and we next need to find out how to get rid of this heat to avoid overheating of the devices.