Introduction to Power Electronics
ECEN 4797/5797

Lecture 8
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In a PWM DC-DC converter:

- The main switch performs the function of conversion of DC power to AC power at the switching frequency.
- The rectifier (diode or synchronous rectifier) performs the function of conversion of AC (switching frequency) power to DC power.

As a result of the above processes, the converter DC voltage and current levels are changed.

The buck converter reduces the dc voltage, and exhibits current gain.

**Buck converter example**

**CCM waveforms**

The buck converter reduces the dc voltage, and exhibits current gain.
Buck converter example

Transistor voltage:
\[ v_{Q1}(t) = V_{Q1} + \tilde{v}_{Q1}(t) \]
where \( V_{Q1} = \langle v_{Q1}(t) \rangle \) (dc component)
and \( \langle \tilde{v}_{Q1}(t) \rangle = 0 \) (\( \tilde{v}_{Q1}(t) \) is the ac component)

Similarly, the transistor current is
\[ i_{Q1}(t) = I_{Q1} + \tilde{i}_{Q1}(t) \]

The power \( p_{Q1}(t) \) flowing into the transistor is:
\[ p_{Q1}(t) = v_{Q1}(t)i_{Q1}(t) = 0 = (V_{Q1} + \tilde{v}_{Q1}(t))(I_{Q1} + \tilde{i}_{Q1}(t)) \]

Now multiply out and average over one period:
\[ 0 = V_{Q1}I_{Q1} + \langle \tilde{v}_{Q1}(t)\tilde{i}_{Q1}(t) \rangle \]

The transistor "consumes" power at DC, and "generates" power at the switching frequency. The transistor functions as an inverter.
\[ V_{Q1}I_{Q1} = -\langle \tilde{v}_{Q1}(t)\tilde{i}_{Q1}(t) \rangle \]
DC components of transistor current and voltage

The transistor voltage is:
\[ v_{Q1}(t) = V_{Q1} + \tilde{v}_{Q1}(t) \]
where
\[ V_{Q1} = h v_{Q1}(t) \]
and
\[ \tilde{v}_{Q1}(t) = 0 \]
(\( \tilde{v}_{Q1}(t) \) is the ac component)

Similarly, the transistor current is
\[ i_{Q1}(t) = I_{Q1} + \tilde{i}_{Q1}(t) \]

The power \( p_{Q1}(t) \) flowing into the transistor is:
\[ p_{Q1}(t) = v_{Q1}(t) i_{Q1}(t) = 0 = V_{Q1} + \tilde{v}_{Q1}(t) \downarrow I_{Q1} + \tilde{i}_{Q1}(t) \uparrow \]

Now multiply out and average over one period:
\[ 0 = V_{Q1} I_{Q1} + h \tilde{v}_{Q1}(t) \tilde{i}_{Q1}(t) \]

The transistor "consumes" power at DC, and "generates" power at the switching frequency. The transistor functions as an inverter.

\[ V_{Q1} I_{Q1} = h \tilde{v}_{Q1}(t) \tilde{i}_{Q1}(t) \]

\[ v_{out}(s) = G(s) (Z(s) + 1)^{-1} Z(s) (Z(s) + 1)^{-1} Z(s) \]

\[ k Z(j!) \]

\[ ZN(j!) \]

\[ ZD(j!) \]

\[ k Z(j!) \]

\[ ZN(j!) \]

\[ ZD(j!) \]
Diode waveforms

![Diode waveforms diagram]

Diode voltage:
\[ v_{D1}(t) = V_{D1} + \tilde{v}_{D1}(t) \]
where \( V_{D1} = \langle v_{D1}(t) \rangle \) (dc component)
and \( \langle \tilde{v}_{D1}(t) \rangle = 0 \) (\( \tilde{v}_{D1}(t) \) is the ac component)

Similarly, the diode current is
\[ i_{D1}(t) = I_{D1} + \tilde{i}_{D1}(t) \]

The power \( p_D(t) \) flowing into the diode is:
\[ p_D(t) = v_{D1}(t)i_{D1}(t) = 0 = (V_{D1} + \tilde{v}_{D1}(t))(I_{D1} + \tilde{i}_{D1}(t)) \]

Now multiply out and average over one period:
\[ 0 = V_{D1}I_{D1} + \langle \tilde{v}_{D1}(t)\tilde{i}_{D1}(t) \rangle \]

Note that \( V_{D1} \) is negative. Hence the diode "consumes" power at the switching frequency, and "generates" power at DC. The diode functions as a rectifier.

\[ V_{D1}I_{D1} = -\langle \tilde{v}_{D1}(t)\tilde{i}_{D1}(t) \rangle \]
Indirect power

The transistor converts power from DC to AC form. This power is transmitted to the diode, which rectifies this AC power to produce DC power.

This power that is converted to AC and then back to DC, is called “indirect power”. The indirect power is equal to:

\[ P_{\text{indirect}} = V_{Q1}I_{Q1} = (DV_{g})(D'I_{L}) = DD'V_{g}I_{L} \]

Lossless or low-loss converters that change the voltage exhibit gain
- Buck converters exhibit current gain
- Boost converters exhibit voltage gain

The indirect power path is responsible for this gain.

For the buck converter: the DC input current is \( I_{Q1} \). The output current \( I_{L} \) is greater than \( I_{Q1} \), by the amount \( I_{D1} \). Rectification of the indirect power by the diode is the mechanism that generates this additional output current.

For the boost converter: the DC input voltage is \( V_{g} \). The output voltage \( V \) is greater than \( V_{g} \), by the amount \( V_{D1} \). Rectification of the indirect power by the diode is the mechanism that generates this additional output voltage.
4.1.5. Synchronous rectifiers

Replacement of diode with a backwards-connected MOSFET, to obtain reduced conduction loss

ideal switch  conventional diode rectifier  MOSFET as synchronous rectifier  instantaneous $i$-$v$ characteristic
Buck converter with synchronous rectifier

- MOSFET $Q_2$ is controlled to turn on when diode would normally conduct.
- Semiconductor conduction loss can be made arbitrarily small, by reduction of MOSFET on-resistances.
- Useful in low-voltage high-current applications.
4.2. A brief survey of power semiconductor devices

- Power diodes
- Power MOSFETs
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs)

- On resistance vs. breakdown voltage vs. switching times
- Minority carrier and majority carrier devices
4.3.1. Transistor switching with clamped inductive load

\[ v_B(t) = v_A(t) - V_g \]

\[ i_A(t) + i_B(t) = i_L \]

Transistor turn-off transition

\[ W_{off} = \frac{1}{2} V_g i_L (t_2 - t_0) \]
Switching loss induced by transistor turn-off transition

Energy lost during transistor turn-off transition:

\[ W_{\text{off}} = \frac{1}{2} V_g i_L (t_2 - t_0) \]

Similar result during transistor turn-on transition. Average power loss:

\[ P_{\text{sw}} = \frac{1}{T_s} \int_{t_{\text{switching}}} p_A(t) \, dt = (W_{\text{on}} + W_{\text{off}}) f_s \]