6.3.2. Forward converter

- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off
Forward converter
with transformer equivalent circuit
Forward converter: waveforms

- Magnetizing current, in conjunction with diode $D_1$, operates in discontinuous conduction mode.
- Output filter inductor, in conjunction with diode $D_3$, may operate in either CCM or DCM.
Subinterval 1: transistor conducts

\[ n_1 : n_2 : n_3 \]

\[ D_1 \text{ off} \quad Q_1 \text{ on} \]

\[ V_g \]

\[ L_M \]

\[ V \]

\[ R \]

\[ C \]
Subinterval 2: transformer reset

\[ V_g \]

\[ i_1 \]

\[ L \]

\[ n_1 : n_2 : n_3 \]

\[ Q_1 \text{ off} \]

\[ i_2 = i_M n_1 / n_2 \]

\[ D_1 \text{ on} \]

\[ D_3 \text{ on} \]

\[ L \]

\[ C \]

\[ R \]

\[ V \]
Subinterval 3

\( Q_1 \text{ off } D_1 \text{ off } \)

\[
\begin{align*}
L_M & = 0 \\
\frac{n_1}{n_2} & = n_3 \\
\]
Magnetizing inductance volt-second balance

\[ \langle v_1 \rangle = D \left( V_g \right) + D_2 \left( -\frac{n_1}{n_2} V_g \right) + D_3(0) = 0 \]
Transformer reset

From magnetizing current volt-second balance:

\[
\langle v_1 \rangle = D (V_g) + D_2 (-V_g n_1/n_2) + D_3 (0) = 0
\]

Solve for \(D_2\):

\[
D_2 = \frac{n_2}{n_1} D
\]

\(D_3\) cannot be negative. But \(D_3 = 1 - D - D_2\). Hence

\[
D_3 = 1 - D - D_2 \geq 0
\]

\[
D_3 = 1 - D \left( 1 + \frac{n_2}{n_1} \right) \geq 0
\]

Solve for \(D\)

\[
D \leq \frac{1}{1 + \frac{n_2}{n_1}}
\]

for \(n_1 = n_2\):

\[D \leq \frac{1}{2}\]
What happens when \( D > 0.5 \)

magnetizing current waveforms, for \( n_1 = n_2 \)

\[
\begin{align*}
D < 0.5 & \quad i_M(t) \\
D > 0.5 & \quad i_M(t)
\end{align*}
\]
Conversion ratio $M(D)$

\[ M(D) = \frac{n_3}{n_1} V_g \]

\[ \langle v_{D3} \rangle = V = \frac{n_3}{n_1} DV_g \]
Maximum duty cycle vs. transistor voltage stress

Maximum duty cycle limited to

\[ D \leq \frac{1}{1 + \frac{n_2}{n_1}} \]

which can be increased by increasing the turns ratio \( n_2 / n_1 \). But this increases the peak transistor voltage:

\[
\max(v_{Q1}) = V_g \left( 1 + \frac{n_1}{n_2} \right)
\]

For \( n_1 = n_2 \)

\[ D \leq \frac{1}{2} \quad \text{and} \quad \max(v_{Q1}) = 2V_g \]
The two-transistor forward converter

\[ V = nDV_g \]
\[ D \leq \frac{1}{2} \]
\[ \max(v_{Q1}) = \max(v_{Q2}) = V_g \]
6.3.4. Flyback converter

**buck-boost converter:**

![Diagram of a buck-boost converter with symbols for Q1, D1, Vg, L, and V.]

**construct inductor winding using two parallel wires:**

![Diagram of a converter with an inductor winding using two parallel wires.]
Derivation of flyback converter, cont.

Isolate inductor windings: the flyback converter

Flyback converter having a 1:n turns ratio and positive output:
The “flyback transformer”

- A two-winding inductor
- Symbol is same as transformer, but function differs significantly from ideal transformer
- Energy is stored in magnetizing inductance
- Magnetizing inductance is relatively small

- Current does not simultaneously flow in primary and secondary windings
- Instantaneous winding voltages follow turns ratio
- Instantaneous (and rms) winding currents do not follow turns ratio
- Model as (small) magnetizing inductance in parallel with ideal transformer

\[
\begin{align*}
V_g & \quad i_g \\
L_M & \quad v_L \\
C & \quad R \\
D_1 & \quad i_C
\end{align*}
\]
Subinterval 1

Transformer model

\[ v_L = V_g \]
\[ i_C = -\frac{V}{R} \]
\[ i_g = I \]

Q₁ on, D₁ off

CCM: small ripple approximation leads to
Subinterval 2

Transformer model

\[ i_g = 0 \]
\[ v_L = -\frac{v}{n} \]
\[ i_C = \frac{i}{n} - \frac{v}{R} \]
\[ i_g = 0 \]

CCM: small ripple approximation leads to

\[ v_L = -\frac{V}{n} \]
\[ i_C = \frac{I}{n} - \frac{V}{R} \]
\[ i_g = 0 \]

Q₁ off, D₁ on
CCM Flyback waveforms and solution

Volt-second balance:
\[ \langle v_L \rangle = D \left( V_g \right) + D' \left( -\frac{V}{n} \right) = 0 \]

Conversion ratio is
\[ M(D) = \frac{V}{V_g} = n \frac{D}{D'} \]

Charge balance:
\[ \langle i_C \rangle = D \left( -\frac{V}{R} \right) + D' \left( \frac{I}{\pi} - \frac{V}{R} \right) = 0 \]

Dc component of magnetizing current is
\[ I = \frac{nV}{D'R} \]

Dc component of source current is
\[ i_g = \langle i_g \rangle = D(I) + D'(0) \]
Equivalent circuit model: CCM Flyback

\[ \langle v_L \rangle = D \left( V_g \right) + D' \left( -\frac{V}{\pi} \right) = 0 \]

\[ \langle i_C \rangle = D \left( -\frac{V}{R} \right) + D' \left( \frac{I}{n} - \frac{V}{R} \right) = 0 \]

\[ I_g = \langle i_g \rangle = D(I) + D'(0) \]
Discussion: Flyback converter

- Widely used in low power and/or high voltage applications
- Low parts count
- Multiple outputs are easily obtained, with minimum additional parts
- Cross regulation is inferior to buck-derived isolated converters
- Often operated in discontinuous conduction mode
- DCM analysis: DCM buck-boost with turns ratio