Equivalent Circuit Model

\[
\langle i_c \rangle = DI_c
\]

\[
\langle v_L \rangle = Dv_g - DI_c R_m + DV - D^2 \ell R_D
\]

\[
- D^2 V - I_c R_L
\]

\[
\langle i_c \rangle = \frac{V}{R}
\]

\[
D^2 R = \left( Dv_g - D^2 V \right) \frac{D^2 R}{D + D^2 R_D + R_L + D^2 R}
\]

\[
M = \frac{V}{v_g} = \frac{-1}{D} \left( D - D^2 \frac{v_D}{v_g} \right) \frac{D^2 R}{D + D^2 R_D + R_L + D^2 R}
\]
\[ M = \frac{-D}{D} \left( 1 - \frac{D}{D} \frac{V_D}{V_g} \right) \frac{D^2 R}{D \rho n + D' R_D + R_c + D'^2 R} \]

Ideal for Buck-Boost

Diode voltage loss:
\[ \frac{D'}{D} \frac{V_D}{V_g} = \frac{V_D}{\frac{d}{dx} V_g} \approx \frac{V_D}{V} \]

Power loss in \( R_c \)
\[ P_{R_c} = I_c^2 R_c \]

Actual power loss
\[ P_{R_c} = I_{rms}^2 R_c \]

\( i_{rms} \geq I_c \) for \( D_i > 0 \)

Model only predicts conduction losses due to average current
Average vs RMS Currents

- Model uses average currents and voltages
- To correctly predict power loss in a resistor, use rms values
- Result is the same, provided ripple is small

**MOSFET current waveforms, for various ripple magnitudes:**

<table>
<thead>
<tr>
<th>Inductor current ripple</th>
<th>MOSFET rms current</th>
<th>Average power loss in $R_{on}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) $\Delta i = 0$</td>
<td>$I \sqrt{D}$</td>
<td>$D f^2 R_{on}$</td>
</tr>
<tr>
<td>(b) $\Delta i = 0.1 I$</td>
<td>$(1.00167)I \sqrt{D}$</td>
<td>$(1.0033) D f^2 R_{on}$</td>
</tr>
<tr>
<td>(c) $\Delta i = I$</td>
<td>$(1.155)I \sqrt{D}$</td>
<td>$(1.3333) D f^2 R_{on}$</td>
</tr>
</tbody>
</table>

Fundamentals of Power Electronics: Chapter 5, Steady-state equivalent circuit modeling, ...
Summary of Chapter 3

1. The dc transformer model represents the primary functions of any dc-dc converter: transformation of dc voltage and current levels, ideally with 100% efficiency, and control of the conversion ratio $M$ via the duty cycle $D$. This model can be easily manipulated and solved using familiar techniques of conventional circuit analysis.

2. The model can be refined to account for loss elements such as inductor winding resistance and semiconductor on-resistances and forward voltage drops. The refined model predicts the voltages, currents, and efficiency of practical nonideal converters.

3. In general, the dc equivalent circuit for a converter can be derived from the inductor volt-second balance and capacitor charge balance equations. Equivalent circuits are constructed whose loop and node equations coincide with the volt-second and charge balance equations. In converters having a pulsating input current, an additional equation is needed to model the converter input port; this equation may be obtained by averaging the converter input current.
Chapter 4: Switch Realization

4.1. Switch applications
    Single-, two-, and four-quadrant switches. Synchronous rectifiers

4.2. A brief survey of power semiconductor devices
    Power diodes, MOSFETs, BJTs, IGBTs, and thyristors

4.3. Switching loss

4.4. Summary of key points
Implementing with SPST Switches

Step 1: Implement circuit with only SPST switches

Also now possible:
A on & B on → Short input source → Bad!
A off & B off → Depends on implementation
if \( i_L > 0 \), OK
- DCM (Chapter 5)

Buck (\( \text{Buck A} \)):
\( V_{\text{off}}: V_g > 0 \)
\( I_{\text{on}}: I_L < 0 \)

Buck with SPDT switch:

with two SPST switches:

Buck (\( \text{Buck A} \)):
\( V_{\text{off}}: -V_g < 0 \)
\( I_{\text{on}}: -I_L < 0 \)
SPST Operating Quadrants

Look at $v(\text{off})$ and $i(\text{on})$

Single-quadrant switch

Current-bidirectional two-quadrant switch

Voltage-bidirectional two-quadrant switch

Four-quadrant switch

Use Chapter 2/3 analysis to get $V_{\text{off}}$, $i_{\text{on}} = f (V_{g}, R, D)$
The Diode

- A passive switch
- Single-quadrant switch:
- can conduct positive on-state current
- can block negative off-state voltage
- provided that the intended on-state and off-state operating points lie on the diode $i$-$v$ characteristic, then switch can be realized using a diode

Symbol instantaneous $i$-$v$ characteristic
(Insulated Gate) Bipolar Junction Transistor

- An active switch, controlled by terminal C
- Single-quadrant switch:
  - can conduct positive on-state current
  - can block positive off-state voltage
- provided that the intended on-state and off-state operating points lie on the transistor $i$-$v$ characteristic, then switch can be realized using a BJT or IGBT

Fundamentals of Power Electronics  Chapter 4: Switch realization
MOSFET

- An active switch, controlled by terminal $C$
- Normally operated as single-quadrant switch:
- can conduct positive on-state current (can also conduct negative current in some circumstances)
- can block positive off-state voltage
- provided that the intended on-state and off-state operating points lie on the MOSFET $i$-$v$ characteristic, then switch can be realized using a MOSFET

Symbol: instantaneous $i$-$v$ characteristic

Fundamentals of Power Electronics 9 Chapter 4: Switch realization
Buck Converter: Switch Realization

From previous analysis:

\[ V = D V_g \]

\[ I_c = \frac{V}{R} = \frac{D V_g}{R} \]

A. \( V_{off}: V_g \rightarrow V_{off} > 0 \)

\( I_{on}: I_c = \frac{D V_g}{R} \rightarrow I_{on} > 0 \)

\( V_{off} \) or \( -V_g \) or \( -\frac{D V_g}{R} \)

B. \( V_{off}: -V_g \rightarrow V_{off} < 0 \)

\( I_{on}: I_c = \frac{D V_g}{R} \rightarrow I_{on} > 0 \)

\( V_{off} \) or \( -V_g \) or \( -\frac{D V_g}{R} \)