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
SPST (single-pole single-throw) switches

SPST switch, with voltage and current polarities defined

All power semiconductor devices function as SPST switches.

Buck converter

with SPDT switch:

with two SPST switches:
Realization of SPDT switch using two SPST switches

- A nontrivial step: two SPST switches are not exactly equivalent to one SPDT switch
- It is possible for both SPST switches to be simultaneously ON or OFF
- Behavior of converter is then significantly modified—discontinuous conduction modes (chapter 5)
- Conducting state of SPST switch may depend on applied voltage or current—for example: diode
Quadrants of SPST switch operation

A single-quadrant switch example:

ON-state: $i > 0$

OFF-state: $v > 0$
Some basic switch applications

Single-quadrant switch

Current-bidirectional two-quadrant switch

Voltage-bidirectional two-quadrant switch

Four-quadrant switch
4.1.1. Single-quadrant switches

**Active switch:** Switch state is controlled exclusively by a third terminal (control terminal).

**Passive switch:** Switch state is controlled by the applied current and/or voltage at terminals 1 and 2.

**SCR:** A special case — turn-on transition is active, while turn-off transition is passive.

**Single-quadrant switch:** on-state $i(t)$ and off-state $v(t)$ are unipolar.
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
The Bipolar Junction Transistor (BJT) and the Insulated Gate Bipolar Transistor (IGBT)

- 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
The Metal-Oxide Semiconductor Field Effect Transistor (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
Realization of switch using transistors and diodes

Buck converter example

Switch A: transistor
Switch B: diode

SPST switch operating points

Switch A

Switch B
Realization of buck converter using single-quadrant switches

\[ V_s \]

\[ i_A + v_A - \]

\[ \begin{array}{c}
L \\
\hline
v_L(t) \\
\hline
\end{array} \]

\[ i_L(t) \]

\[ v_B + \]

\[ i_B \]

\[ \begin{array}{c}
\text{Switch A on} \\
\hline
\text{Switch A off} \]

\[ \begin{array}{c}
\text{Switch B on} \\
\hline
\text{Switch B off} \]

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4.1.2. Current-bidirectional two-quadrant switches

- Usually an active switch, controlled by terminal $C$
- Normally operated as two-quadrant switch:
  - can conduct positive or negative on-state current
  - can block positive off-state voltage
- provided that the intended on-state and off-state operating points lie on the composite $i$-$v$ characteristic, then switch can be realized as shown
Two quadrant switches

- On-state (transistor conducts): $v \leq 0$, $i \geq 0$
- Off-state (diode conducts): $v \leq 0$, $i \leq 0$

The diagram illustrates the switch states and their corresponding current and voltage conditions.
MOSFET body diode

Power MOSFET characteristics

Power MOSFET, and its integral body diode

Use of external diodes to prevent conduction of body diode

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A simple inverter

\[ v_0(t) = (2D - 1) V_g \]
Inverter: sinusoidal modulation of $D$

$$v_0(t) = (2D - 1) V_g$$

Sinusoidal modulation to produce ac output:

$$D(t) = 0.5 + D_m \sin(\omega t)$$

The resulting inductor current variation is also sinusoidal:

$$i_L(t) = \frac{v_0(t)}{R} = (2D - 1) \frac{V_g}{R}$$

Hence, current-bidirectional two-quadrant switches are required.
The dc-3øac voltage source inverter (VSI)

Switches must block dc input voltage, and conduct ac load current.
Bidirectional battery charger/discharger

A dc-dc converter with bidirectional power flow.
4.1.3. Voltage-bidirectional two-quadrant switches

- Usually an active switch, controlled by terminal \( C \)
- Normally operated as two-quadrant switch:
  - can conduct positive on-state current
  - can block positive or negative off-state voltage
- provided that the intended on-state and off-state operating points lie on the composite \( i-v \) characteristic, then switch can be realized as shown
- The SCR is such a device, without controlled turn-off

**Diagram:**

- BJT / series diode realization
- instantaneous \( i-v \) characteristic
- \( i \) axis
- \( v \) axis
- \( C \) terminal
- \( i \) current
- \( v \) voltage
- \( 0 \) threshold level
- \( + \) positive
- \( - \) negative
- off (diode blocks voltage)
- off (transistor blocks voltage)
Two-quadrant switches

- **On-state current**: The switch is conducting current in the forward direction.
- **Off-state voltage**: The switch is blocking voltage in the reverse direction.

**Diode**: Blocks voltage in the reverse direction.

**Transistor**: Blocks voltage in the reverse direction.

Diagram showing the directions of current and voltage for both on-state and off-state conditions.
A dc-3Øac buck-boost inverter

Requires voltage-bidirectional two-quadrant switches.

Another example: boost-type inverter, or current-source inverter (CSI).
4.1.4. Four-quadrant switches

- Usually an active switch, controlled by terminal C
- can conduct positive or negative on-state current
- can block positive or negative off-state voltage
Three ways to realize a four-quadrant switch
A 3øac-3øac matrix converter

- All voltages and currents are ac; hence, four-quadrant switches are required.
- Requires nine four-quadrant switches
Power Processing Functions of a Switch

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

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

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

DC component of $v_{Q1}(t)$

$V_{Q1} = D'V_s$

DC component of $i_{Q1}(t)$

$I_{Q1} = DI_L$

$V_{Q1}$ (DC component)

$\tilde{v}_{Q1}(t)$ (ac component)

$i_{Q1}$ (DC component)

$\tilde{i}_{Q1}(t)$ (ac component)

$V_s$

$T_s$

$DT_s$

MOSFET on

MOSFET off
Similarly, the transistor current is
\[ i_{Q(t)} = v_{Q(t)} - v_D(L) + i_L \]
where \( v_{Q(t)} = \langle v_D(t) \rangle \) (dc component)
and \( \langle \tilde{v}_D(t) \rangle = 0 \) (\( \tilde{v}_D(t) \) is the ac component)
Similarly, the diode current is
\[ i_{D(t)} = I_{D(t)} + \tilde{i}_{D(t)} \]
The power \( p_D(t) \) flowing into the diode is:
\[ p_D(t) = v_{D(t)}i_{D(t)} = 0 = (V_{D1} + \tilde{v}_{D1}(t)) (I_{D1} + \tilde{i}_{D1}(t)) \]
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:

\[ P_{\text{indirect}} = V_{Q1}I_{Q1} = (DV_g)(D'I_L) = DD'V_gI_L \]

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