Switch Realization

Switch applications

Single-, two-, and four-quadrant switches. Synchronous rectifiers

A brief survey of power semiconductor devices

Power diodes, MOSFETs, BJTs, IGBTs, and thyristors

Switching loss

SPST (single-pole single-throw) switches

**SPST switch, with voltage and current polarities defined**

![SPST switch diagram]

All power semiconductor devices function as SPST switches.

**Buck converter**

*with SPDT switch:*

![Buck converter with SPDT switch]

*with two SPST switches:*

![Buck converter with two SPST switches]

Fundamentals of Power Electronics  
Switch realization
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 (ch. 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)

- **Symbol**: instantaneous $i-v$ characteristic

- **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

SPST switch operating points

Switch A: transistor
Switch B: diode

Fundamentals of Power Electronics  Switch realization
Realization of buck converter using single-quadrant switches

\[ V_g \]

\[ i_A \]

\[ +v_A \]

\[ - \]

\[ L \]

\[ +v_L(t) \]

\[ -v_L(t) \]

\[ i_L(t) \]

\[ i_B \]

\[ +v_B \]

\[ - \]

\[ i_B \]

\[ v_B \]

\[ v_A \]

\[ v_L(t) \]

\[ V_g \]

\[ + \]

\[ - \]

\[ i_A \]

\[ i_L \]

\[ i_B \]

\[ i_L \]

\[ v_B \]

\[ v_A \]

\[ V_g \]

\[ -V_g \]
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

BJT / anti-parallel diode realization

instantaneous $i$-$v$ characteristic
Two quadrant switches

- **on**: (transistor conducts)
- **off**: (diode conducts)

Diagram showing the on and off states of a switch with current (i) and voltage (v) axes.
MOSFET body diode

Power MOSFET characteristics

Power MOSFET, and its integral body diode

Use of external diodes to prevent conduction of body diode

Fundamentals of Power Electronics

Switch realization
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.
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**
Two-quadrant switches

- **Switch realization**
- **Diode blocks voltage**
- **Transistor blocks voltage**
- **On-state current**
- **Switch on-state current**
- **Switch off-state voltage**
A dc-3øac buck-boost inverter

Requires voltage-bidirectional two-quadrant switches.

Another example: boost-type inverter, or current-source inverter (CSI).
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
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

\[ i \]
\[ v \]

on (reverse conduction)

on
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
Power diodes

A power diode, under reverse-biased conditions:

![Diagram showing a power diode with a depletion region, reverse-biased with low doping concentration.]

E - depletion region, reverse-biased

$E$ - potential energy

$v$ - voltage

$+\rightarrow -$ - reverse bias

Fundamentals of Power Electronics  Switch realization
Forward-biased power diode

conductivity modulation

minority carrier injection
Typical diode switching waveforms

\[ \text{Fundamentals of Power Electronics} \]

\[ \text{Switch realization} \]
The Power MOSFET

- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown
MOSFET: Off state

- $p$-$n^-$ junction is reverse-biased
- Off-state voltage appears across $n^-$ region

Fundamentals of Power Electronics  Switch realization
MOSFET: on state

- $p-n^-$ junction is slightly reverse-biased
- Positive gate voltage induces conducting channel
- Drain current flows through $n^-$ region and conducting channel
- On resistance = total resistances of $n^-$ region, conducting channel, source and drain contacts, etc.
MOSFET body diode

- $p$-$n$ junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized —body diode is slow, $Q_r$ is large
Typical MOSFET characteristics

- Off state: $V_{GS} < V_{th}$
- On state: $V_{GS} >> V_{th}$
- MOSFET can conduct peak currents well in excess of average current rating — characteristics are unchanged
- on-resistance has positive temperature coefficient, hence easy to parallel

![Graph showing MOSFET characteristics with voltage and current values](image-url)
A simple MOSFET equivalent circuit

- $C_{gs}$: large, essentially constant
- $C_{gd}$: small, highly nonlinear
- $C_{ds}$: intermediate in value, highly nonlinear
- Switching times determined by rate at which gate driver charges/discharges $C_{gs}$ and $C_{gd}$

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0}{\sqrt{v_{ds}}}$$
4.2.3. Bipolar Junction Transistor (BJT)

- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in \( p \) and \( n^- \) regions, conductivity modulation
BJT switching times

\[ \begin{align*}
V_{CC} & \quad R_L \\
\downarrow & \quad \downarrow \\
i_C(t) & \quad + \\
& \quad - \\
v_{CE}(t) & \\
& \quad + \\
& \quad - \\
\downarrow & \quad \downarrow \\
i_B(t) & \quad R_B \\
\& \quad \& \\
v_{BE}(t) & \quad + \\
& \quad - \\
& \quad + \\
& \quad - \\
\downarrow & \quad \downarrow \\
v_S(t) & \quad + \\
& \quad - \\
\end{align*} \]
Ideal base current waveform
Current crowding due to excessive $I_{B2}$

can lead to formation of hot spots and device failure
BJT characteristics

- Off state: $I_B = 0$
- On state: $I_B > I_C / \beta$
- Current gain $\beta$ decreases rapidly at high current. Device should not be operated at instantaneous currents exceeding the rated value
Breakdown voltages

$BV_{CEO}$: avalanche breakdown voltage of base-collector junction, with the emitter open-circuited

$BV_{CEO}$: collector-emitter breakdown voltage with zero base current

$BV_{sus}$: breakdown voltage observed with positive base current

In most applications, the off-state transistor voltage must not exceed $BV_{CEO}$. 

$IC$...
4.2.4. The Insulated Gate Bipolar Transistor (IGBT)

- A four-layer device
- Similar in construction to MOSFET, except extra \( p \) region
- On-state: minority carriers are injected into \( n^- \) region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)
The IGBT

Symbol

Location of equivalent devices

Fundamentals of Power Electronics
Current tailing in IGBTs

\[ i_L(t) = v_A \cdot i_A \]

\[ p_A(t) = v_A \cdot i_A \]

Diagram showing IGBT and diode waveforms with current tailing and area \( W_{off} \).
**Snubber**

**Definition:** Snubber is a circuit connected around a power device to alter its switching trajectory.

**Advantages:**
- Reduce switching power loss
- Avoid 2nd breakdown
- Control $dv/dt$ and $di/dt$ to avoid latching in pnpn devices
\[ i_{sw} = I_L \left( 1 - \frac{t}{t_f} \right) \quad \text{(Assuming linear fall)} \]

\[ C \frac{dv_c}{dt} = i_c = I_L - i_{sw} = I_L \left( \frac{t}{t_f} \right) \]

\[ W_{sw} = \int_0^{t_f} v_c i_{sw} \, dt = \int_0^{t_f} v_c i_{sw} \, dt = \int_0^{t_f} I_L \frac{t^2}{C} I_L \left( 1 - \frac{t}{t_f} \right) dt = \frac{I_L^2}{24C} t_f^2 \]

- In addition an energy \[ \frac{1}{2} CV_{off}^2 \] will be lost in the resistor as the charge dissipates.

\[ P_{sw} = \left( \frac{I_L^2}{24C} t_f^2 + \frac{1}{2} CV_{off}^2 \right) f_{sw} \]

- \( P_{sw} \) (Inductive commutation) = \[ \frac{\left( V_{off} I_L t_f f_{sw} \right)}{2} \]

Thus snubber will decrease the switching loss as compared to the inductive loss if

\[ \frac{I_L^2}{12C} t_f^2 + CV_{off}^2 < V_{off} I_L t_f \]
MOSFET Bipolar Secondary Breakdown

- The secondary breakdown refers to a sudden reduction in the blocking voltage capability when the drain current increases.
- A deep p+ diffusion in the center of the DMOS cell can be used to reduce $R_B$ and prevent the occurrence of secondary breakdown.

Current Paths in power MOSFET with Activated parasitic bipolar transistor
Possible Switch Arrangements

Type 1
- CONSTANT DC BUS
- High Side Switch
- Low Side Switch
- GROUND

Type 2
- CONSTANT DC BUS
- High Side Switches
- Low Side Switch
- GROUND
Possible Switch Arrangements (contd..)

Type 3

Floating Rail

All Switches are High Side

Floating Rail
Commonly Used Gate Driver Types

• Low Side Drivers

• High Side Drivers
  – Optoisolator Type (Can be used for Types 1, 2 and 3)
  – Pulse Transformer Type (Can be used for Types 1, 2 and 3)
  – Bootstrap (Can be used for Type 1 only)
  – Charge Pump (Can be used for Type 1 only)
Optoisolator based gate driver

Optoisolator

HCPL-2630

Gate Driver #1

Gate Driver #2

To HS Switch

Vin1

GND

Vin2

GND
Pulse Transformer based gate driver

- Pulse Transformer based gate driver can be used for high side or low side devices
- Simple toroids can be used for building the pulse transformers
- Pulse transformer magnetizing current must be reset in every cycle
Bootstrap Gate Drive

**Features**
- Simple implementation
- Requires level shifter
- Cannot operate at high duty ratios
- High power dissipation

**Operation**
- Gate charge for high-side MOSFET is provided by bootstrap capacitor
- Bootstrap capacitor is charged through the bootstrap diode

(Typical Connection)

(Refer to Lead Assignments for correct pin configuration). This diagram(s) show electrical connections only. Please refer to our Application Notes and DesignTips for proper circuit board layout.
Bootstrap Gate Driver

\[ C_{\text{boot}} \geq \frac{2[2Q_g + Q_{ls}]}{V_{cc} - V_f - V_{LS} - V_{\text{Min}}} \]

- \( Q_g \): Gate charge of high side FET
- \( f \): Frequency of operation
- \( V_f \): Forward voltage drop across the bootstrap diode
- \( V_{LS} \): Voltage drop across the low side FET or load
- \( Q_{ls} \): Level shift charge required per cycle
Charge-Pump Gate Driver

- Features
  - Can be used to generate “over rail” voltage to pump the gate drive when MOSFET is ON
  - Gate can be kept on for an indefinite period of time
  - Inefficiencies in voltage multiplication circuit
transfer charge to the gate of the power Mosfet able then to reach, at the voltage transition end, a level equal to \( V_{\text{supply}} + V_{\text{Aux}} \).

From this condition on, the oscillator, running as long as the power switch is ON, periodically refreshes the gate voltage compensating all the present losses.

In the case of circuits intended to work at lower supply voltage, the doubler can be modified into a voltage tripler roughly represented in Fig. 5.24.

Always disregarding all diodes forward voltage drop, \( C_1 \) is charged to \( 2 \, V_{\text{aux}} \), \( C \), to \( \frac{3}{2} \, V_{\text{aux}} \).
Charge-Pump Gate Driver
Diode recovered charge

- Diode recovered stored charge $Q_r$ flows through transistor during transistor turn-on transition, inducing switching loss
- $Q_r$ depends on diode on-state forward current, and on the rate-of-change of diode current during diode turn-off transition
Switching loss calculation

Energy lost in transistor:

\[ W_D = \int_{t_0}^{t_1} v_A(t) \, i_A(t) \, dt \]

With abrupt-recovery diode:

\[ W_D \approx \int_{t_0}^{t_1} V_g (i_L - i_B(t)) \, dt \]

\[ = V_g \, i_L \, t_r + V_g \, Q_r \]

- Often, this is the largest component of switching loss

Soft-recovery diode:

\[ (t_2 - t_1) >> (t_1 - t_0) \]

Abrupt-recovery diode:

\[ (t_2 - t_1) << (t_1 - t_0) \]
Device capacitances, and leakage, package, and stray inductances

- Capacitances that appear effectively in parallel with switch elements are shorted when the switch turns on. Their stored energy is lost during the switch turn-on transition.

- Inductances that appear effectively in series with switch elements are open-circuited when the switch turns off. Their stored energy is lost during the switch turn-off transition.

Total energy stored in linear capacitive and inductive elements:

\[
W_C = \sum_{\text{capacitive elements}} \frac{1}{2} C_i V_i^2 \\
W_L = \sum_{\text{inductive elements}} \frac{1}{2} L_j I_j^2
\]
Example: semiconductor output capacitances

Buck converter example

Energy lost during MOSFET turn-on transition (assuming linear capacitances):

$$W_C = \frac{1}{2} (C_{ds} + C_j) V_g^2$$
MOSFET nonlinear $C_{ds}$

Approximate dependence of incremental $C_{ds}$ on $v_{ds}$:

$$C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0}{\sqrt{v_{ds}}}$$

Energy stored in $C_{ds}$ at $v_{ds} = V_{DS}$:

$$W_{Cds} = \int v_{ds} i_C \, dt = \int_0^{V_{DS}} v_{ds} C_{ds}(v_{ds}) \, dv_{ds}$$

$$W_{Cds} = \int_0^{V_{DS}} C'_0(v_{ds}) \sqrt{v_{ds}} \, dv_{ds} = \frac{2}{3} C_{ds}(V_{DS}) V_{DS}^2$$

— same energy loss as linear capacitor having value $\frac{4}{3} C_{ds}(V_{DS})$
Some other sources of this type of switching loss

Schottky diode
- Essentially no stored charge
- Significant reverse-biased junction capacitance

Transformer leakage inductance
- Effective inductances in series with windings
- A significant loss when windings are not tightly coupled

Interconnection and package inductances
- Diodes
- Transistors
- A significant loss in high current applications
Ringing induced by diode stored charge

- Diode is forward-biased while $i_L(t) > 0$
- Negative inductor current removes diode stored charge $Q_r$
- When diode becomes reverse-biased, negative inductor current flows through capacitor $C$.
- Ringing of $L$-$C$ network is damped by parasitic losses. Ringing energy is lost.
Energy associated with ringing

Recovered charge is

\[ Q_r = - \int_{t_2}^{t_3} i_L(t) \, dt \]

Energy stored in inductor during interval \( t_2 \leq t \leq t_3 \):

\[ W_L = \int_{t_2}^{t_3} v_L(t) \, i_L(t) \, dt \]

Applied inductor voltage during interval \( t_2 \leq t \leq t_3 \):

\[ v_L(t) = L \frac{di_L(t)}{dt} = -V_2 \]

Hence,

\[ W_L = \int_{t_2}^{t_3} L \frac{di_L(t)}{dt} i_L(t) \, dt = \int_{t_2}^{t_3} (-V_2) \, i_L(t) \, dt \]

\[ W_L = \frac{1}{2} L i^2_L(t_3) = V_2 Q_r \]
Efficiency vs. switching frequency

Add up all of the energies lost during the switching transitions of one switching period:

$$W_{tot} = W_{on} + W_{off} + W_D + W_C + W_L + \ldots$$

Average switching power loss is

$$P_{sw} = W_{tot} f_{sw}$$

Total converter loss can be expressed as

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot} f_{sw}$$

where

- $P_{fixed} = \text{fixed losses (independent of load and } f_{sw})$
- $P_{cond} = \text{conduction losses}$
Efficiency vs. switching frequency

\[ P_{\text{loss}} = P_{\text{cond}} + P_{\text{fixed}} + W_{\text{tot}} f_{\text{sw}} \]

Switching losses are equal to the other converter losses at the critical frequency

\[ f_{\text{crit}} = \frac{P_{\text{cond}} + P_{\text{fixed}}}{W_{\text{tot}}} \]

This can be taken as a rough upper limit on the switching frequency of a practical converter. For \( f_{\text{sw}} > f_{\text{crit}} \), the efficiency decreases rapidly with frequency.