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

All power semiconductor devices function as 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
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

SPST switch operating points

Switch A: transistor
Switch B: diode

Realization of buck converter using single-quadrant switches

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

- **Switch on-state current:**
  - When the transistor conducts, the current flows through it.
  - Symbol: $i_{on}$

- **Switch off-state voltage:**
  - When the diode conducts, the voltage across it is negligible.
  - Symbol: $v_{off}$

MOSFET body diode

- **Power MOSFET characteristics:**
  - The transistor conducts.

- **Power MOSFET and its integral body diode:**
  - Symbol: $i_{D}$

- **Use of external diodes to prevent conduction of body diode:**

A simple inverter

- **Inverter diagram:**
  - Symbols: $V_{in}$, $i_L$, $v_0(t)$, $D_1$, $D_2$, $R$, $C$

- **Equation:**
  - $v_0(t) = (2D - 1)V_{in}$
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

Two-quadrant switches

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
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

4.2. A brief survey of power semiconductor devices

- Power diodes
- Power MOSFETs
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs)
- Thyristors (SCR, GTO, MCT)

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

\[ V_{\text{gs}} = \frac{1}{2} V_i L (t_2 - t_1) \]

Switching loss induced by transistor turn-off transition

Energy lost during transistor turn-off transition:

\[ W_{\text{off}} = \frac{1}{2} V_i L (t_2 - t_1) \]

Similar result during transistor turn-on transition.

Average power loss:

\[ P_{\text{sw}} = \frac{1}{T_s} \int_{t_0}^{t_1} p_s(t) \, dt = (W_{\text{on}} + W_{\text{off}}) f_s \]

4.2.1. Power diodes

A power diode, under reverse-biased conditions:
Typical diode switching waveforms

Forward-biased power diode

Charge-controlled behavior of the diode

The diode equation:

\[ q(t) = Q_0 e^{(\lambda v(t) - 1)} \]

Charge control equation:

\[ \frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L} \]

With:

\[ \lambda = \frac{1}{26 \text{ mV}} \text{ at } 300 \text{ K} \]

\[ \tau_L = \text{minority carrier lifetime} \]

(above equations don’t include current that charges depletion region capacitance)

In equilibrium: \[ dq(t)/dt = 0 \] and hence

\[ i(t) = \frac{Q_0}{\tau_L} e^{(\lambda v(t) - 1)} = L \left( e^{\lambda v(t)} - 1 \right) \]
Charge-control in the diode: Discussion

- The familiar $i$–$v$ curve of the diode is an equilibrium relationship that can be violated during transient conditions.
- During the turn-on and turn-off switching transients, the current deviates substantially from the equilibrium $i$–$v$ curve, because of change in the stored charge and change in the charge within the reverse-bias depletion region.
- Under forward-biased conditions, the stored minority charge causes "conductivity modulation" of the resistance of the lightly-doped $n$– region, reducing the device on-resistance.

Diode in OFF state: reversed-biased, blocking voltage

- Diode is reverse-biased.
- No stored minority charge, $q = 0$.
- Depletion region blocks applied reverse voltage; charge is stored in capacitance of depletion region.

Turn-on transient

The current $i(t)$ is determined by the converter circuit. This current supplies:
- charge to increase voltage across depletion region
- charge needed to support the on-state current
- charge to reduce on-resistance of $n$– region.
### Turn-off transient

Turn-off transient

![Diode turn-off transient](image)

- **Removal of stored minority charge**
- **i** (< 0)
- **v**

### Diode turn-off transient continued

Diode turn-off transient continued

![Diode turn-off transient](image)

- **Area**
- **–Qr**
- **v**
- **tr**

### The diode switching transients induce switching loss in the transistor

The diode switching transients induce switching loss in the transistor

- **Diode recovered stored charge**
- **Qr** flows through transistor during transistor turn-on transition, inducing switching loss
- **Qr** 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:

\[ W_D = \int_{t_0}^{t_1} v_d(t) i_d(t) dt \]

With abrupt-recovery diode:

\[ W_D = \int_{t_0}^{t_1} V_D i_d(t) dt \]

\[ = V_D i_d(t_1) + V_D Q_r \]

- Often, this is the largest component of switching loss

Soft-recovery diode:

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

Abrupt-recovery diode:

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

Types of power diodes

**Standard recovery**
- Reverse recovery time not specified, intended for 50/60Hz

**Fast recovery and ultra-fast recovery**
- Reverse recovery time and recovered charge specified
- Intended for converter applications

**Schottky diode**
- A majority carrier device
- Essentially no recovered charge
- Model with equilibrium \( i-v \) characteristic, in parallel with depletion region capacitance
- Restricted to low voltage (few devices can block 100V or more)

Characteristics of several commercial power rectifier diodes

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>( V_f ) (typical)</th>
<th>( t_r ) (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast recovery rectifiers</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1N3913</td>
<td>400V</td>
<td>30A</td>
<td>1.1V</td>
<td>400ns</td>
</tr>
<tr>
<td>1N5408</td>
<td>200V</td>
<td>40A</td>
<td>1.2V</td>
<td>2µs</td>
</tr>
<tr>
<td>Ultrafast recovery rectifiers</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUR15</td>
<td>150V</td>
<td>3A</td>
<td>0.375V</td>
<td>10ns</td>
</tr>
<tr>
<td>MUR160</td>
<td>600V</td>
<td>15A</td>
<td>1.2V</td>
<td>80ns</td>
</tr>
<tr>
<td>300A/500</td>
<td>1200V</td>
<td>100A</td>
<td>2.0V</td>
<td>90ns</td>
</tr>
<tr>
<td>Schottky rectifiers</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBR6030L</td>
<td>600V</td>
<td>30A</td>
<td>0.45V</td>
<td></td>
</tr>
<tr>
<td>444CNQ045</td>
<td>45V</td>
<td>440A</td>
<td>0.40V</td>
<td></td>
</tr>
<tr>
<td>30CPQ150</td>
<td>150V</td>
<td>30A</td>
<td>1.15V</td>
<td></td>
</tr>
</tbody>
</table>
Paralleling diodes

Attempts to parallel diodes and share the current so that \( i_1 = i_2 = \frac{i}{2} \), generally don't work.

Reason: thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

To get the diodes to share the current, heroic measures are required:

- Select matched devices
- Package on common thermal substrate
- Build external circuitry that forces the currents to balance

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 \( Q_r = - \int i_L(t) \, dt \).

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

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

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

\[
\dot{v}_L(t) = \frac{d}{dt} v_L(t) = -V_2
\]

Hence,

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

\[
W_L = \frac{1}{2} L i_L^2(t_3) = V_2 Q_r
\]
4.2.2. 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

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.

**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 rates at which gate driver charges/discharges $C_{gs}$ and $C_{gd}$.

$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1 + \frac{v_{ds}}{V_0}}}$$

$$C_{gs}(v_{gs}) = C_0 \sqrt{1 + \frac{v_{gs}}{V_0}} = \frac{C_0}{v_{gs}}$$
Switching loss caused by semiconductor output capacitances

**Buck converter example**

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

\[ W_i = \frac{1}{2} (C_{ds} + C_j) V_g^2 \]

**MOSFET nonlinear \( C_{ds} \)**

Approximate dependence of incremental \( C_{ds} \) on \( V_{ds} \):

\[ C_{ds}(V_{ds}) = C_0 + V_{ds} \frac{dV}{dn} \]

Energy stored in \( C_{ds} \) at \( V_{ds} = V_{DS} \):

\[ W_{ds} = \int_{V_{ds}}^{V_{DS}} V_{ds} C_{ds} dV_{ds} \]

\[ W_{ds} = \frac{1}{2} C_0 V_{DS}^2 + \frac{1}{2} C_j V_{DS}^2 \]

--- same energy loss as linear capacitor having value \( \frac{1}{2} C_j(V_{ds}) \)

**Characteristics of several commercial power MOSFETs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rated max voltage</th>
<th>Rated max current</th>
<th>( R_s )</th>
<th>( Q_i ) (micros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ48</td>
<td>60V</td>
<td>50A</td>
<td>0.018Ω</td>
<td>11μC</td>
</tr>
<tr>
<td>IRF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54Ω</td>
<td>8.3μC</td>
</tr>
<tr>
<td>IRF540</td>
<td>100V</td>
<td>28A</td>
<td>0.077Ω</td>
<td>72μC</td>
</tr>
<tr>
<td>APT10M25BN</td>
<td>100V</td>
<td>75A</td>
<td>0.025Ω</td>
<td>175μC</td>
</tr>
<tr>
<td>IRF750</td>
<td>400V</td>
<td>10A</td>
<td>0.5Ω</td>
<td>63μC</td>
</tr>
<tr>
<td>IRF7500</td>
<td>400V</td>
<td>15A</td>
<td>0.3Ω</td>
<td>110μC</td>
</tr>
<tr>
<td>APT15025BN</td>
<td>600V</td>
<td>21A</td>
<td>0.2Ω</td>
<td>83μC</td>
</tr>
<tr>
<td>APT1001RBN</td>
<td>1000V</td>
<td>11A</td>
<td>1.0Ω</td>
<td>150μC</td>
</tr>
</tbody>
</table>
MOSFET: conclusions

- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating

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

- 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
Ideal base current waveform

Current crowding due to excessive $I_{B2}$

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

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

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

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

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

Darlington-connected BJT

- Increased current gain, for high-voltage applications
- In a monolithic Darlington device, transistors $Q_1$ and $Q_2$ are integrated on the same silicon wafer
- Diode $D_1$ speeds up the turn-off process, by allowing the base driver to actively remove the stored charge of both $Q_1$ and $Q_2$ during the turn-off transition

Conclusions: BJT

- BJT has been replaced by MOSFET in low-voltage (<500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V
- A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages
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

Current tailing in IGBTs
**Switching loss due to current-tailing in IGBT**

Example: buck converter with IGBT

\[ P_{sw} = \int_{t_0}^{t_1} p(t) dt = (W_{on} + W_{off}) f_s \]

**Characteristics of several commercial devices**

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>( V_f ) (typical)</th>
<th>( t_f ) (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single-chip devices</strong></td>
<td></td>
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</tr>
<tr>
<td>HGTG32N60E2</td>
<td>600V</td>
<td>32A</td>
<td>2.4V</td>
<td>0.62µs</td>
</tr>
<tr>
<td>HGTG30N120D2</td>
<td>1200V</td>
<td>30A</td>
<td>3.2A</td>
<td>0.58µs</td>
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<td><strong>Multiple-chip power modules</strong></td>
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</tr>
<tr>
<td>CM400HA-12E</td>
<td>600V</td>
<td>400A</td>
<td>2.7V</td>
<td>0.3µs</td>
</tr>
<tr>
<td>CM300HA-24E</td>
<td>1200V</td>
<td>300A</td>
<td>2.7V</td>
<td>0.3µs</td>
</tr>
</tbody>
</table>

**Conclusions: IGBT**

- Becoming the device of choice in 500 to 1700V+ applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current —easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance; 2-4V typical
- Easy to drive —similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing:
  - 3300 V devices: HVIGBTs
  - 150 kHz switching frequencies in 800 V devices
4.2.5. Thyristors (SCR, GTO, MCT)

**The SCR**

- **Symbol:**
  - Anode (A)
  - Gate (G)
  - Cathode (K)

- **Equivalent Circuit**
  - Forward conduction
  - Reverse blocking

- **Construction**
  - Large feature size
  - Negative gate current induces lateral voltage drop along gate-cathode junction
  - Gate-cathode junction becomes reverse-biased only in vicinity of gate contact

The Silicon Controlled Rectifier (SCR)

- Positive feedback — a latching device
- A minority carrier device
- Double injection leads to very low on-resistance, hence low forward voltage drops attainable in very high voltage devices
- Simple construction, with large feature size
- Cannot be actively turned off
- A voltage-bidirectional two-quadrant switch
- 5000-6000V, 1000-2000A devices

Why the conventional SCR cannot be turned off via gate control

- Large feature size
- Negative gate current induces lateral voltage drop along gate-cathode junction
- Gate-cathode junction becomes reverse-biased only in vicinity of gate contact
The Gate Turn-Off Thyristor (GTO)
- An SCR fabricated using modern techniques — small feature size
- Gate and cathode contacts are highly interdigitated
- Negative gate current is able to completely reverse-bias the gate-cathode junction

Turn-off transition:
- Turn-off current gain: typically 2-5
- Maximum controllable on-state current: maximum anode current that can be turned off via gate control. GTO can conduct peak currents well in excess of average current rating, but cannot switch off

The MOS-Controlled Thyristor (MCT)
- Still an emerging device, but some devices are commercially available
- p-type device
- A latching SCR, with added built-in MOSFETs to assist the turn-on and turn-off processes
- Small feature size, highly interdigitated, modern fabrication

The MCT: equivalent circuit
- Negative gate-anode voltage turns p-channel MOSFET \( Q_3 \) on, causing \( Q_1 \) and \( Q_2 \) to latch on
- Positive gate-anode voltage turns n-channel MOSFET \( Q_4 \) on, reverse-biasing the base-emitter junction of \( Q_2 \) and turning off the device
- Maximum current that can be interrupted is limited by the on-resistance of \( Q_4 \)
Summary: Thyristors

- The thyristor family: double injection yields lowest forward voltage drop in high voltage devices. More difficult to parallel than MOSFETs and IGBTs
- The SCR: highest voltage and current ratings, low cost, passive turn-off transition
- The GTO: intermediate ratings (less than SCR, somewhat more than IGBT). Slower than IGBT. Slower than MCT. Difficult to drive.
- The MCT: So far, ratings lower than IGBT. Slower than IGBT. Easy to drive. Second breakdown problems? Still an emerging device.

4.3. Switching loss

- Energy is lost during the semiconductor switching transitions, via several mechanisms:
  - Transistor switching times
  - Diode stored charge
  - Energy stored in device capacitances and parasitic inductances
  - Semiconductor devices are charge controlled
  - Time required to insert or remove the controlling charge determines switching times

4.3.1. Transistor switching with clamped inductive load

Buck converter example

\[ v_f(t) = v_i(t) - V_i \]
\[ v_f(t) + v_d(t) = i_L \]
\[ W_{off} = \frac{1}{2} V_i (t_2 - t_1) \]
Switching loss induced by transistor turn-off transition

Energy lost during transistor turn-off transition:

\[ W_{off} = \frac{1}{2} V_{giL} (t_2 - t_0) \]

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

\[ P_{sw} = \frac{1}{f_s} \int_{t_0}^{t_2} p_{sw}(t) \, dt = (W_{on} + W_{off}) f_s \]

Switching loss due to current-tailing in IGBT

Example: buck converter with IGBT

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:

\[ W_T = \int v_d(t) i_d(t) \, dt \]

With abrupt-recovery diode:

\[ W_T = \int v_v(t) i_v(t) \, dt \]

\[ = V_g i_L(t) + V_r Q_r \]

- Often, this is the largest component of switching loss

Soft-recovery diode:

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

Abrupt-recovery diode:

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

4.3.3. 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:

\[ W_C = \frac{1}{2} \sum C_i V_i^2 \]

\[ W_L = \frac{1}{2} \sum L_i I_i^2 \]

Example: semiconductor output capacitances

Back converter example

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

\[ W_T = \frac{1}{2} (C_j + C) V_g^2 \]
MOSFET nonlinear \( C_{ds} \)

Approximate dependence of incremental \( C_{ds} \) on \( v_{ds} \):

\[
C_d(v_{ds}) = C_0 \left( \sqrt{\frac{v_{ds}}{V_0}} + \frac{v_{ds}}{V_0^2} \right)
\]

Energy stored in \( C_{ds} \) at \( v_{ds} = V_{DS} \):

\[
W_{ds} = \int v_{ds} \cdot C_{ds} \, dv_{ds} = \frac{1}{2} C_{ds}(V_{DS}) \cdot V_{DS}
\]

\( - \) same energy loss as linear capacitor having value \( 4 \cdot C_{ds}(V_{DS}) \)

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: \[ Q_r = -\int_{t_1}^{t_2} v_1(t) \, dt \]

Energy stored in inductor during interval \( t_2 \leq t \leq t_3 \):
\[ W_i = \int_{t_2}^{t_3} (\frac{dv}{dt}) \, dt = \int_{t_2}^{t_3} (V_2 - V_i(t)) \, dt \]

Applied inductor voltage during interval \( t_2 \leq t \leq t_3 \):
\[ v_i(t) = \frac{dI_L(t)}{dt} = \frac{V_2(t) - V_i(t)}{L} \]

Hence,
\[ W_i = \frac{1}{2} L \int_{t_2}^{t_3} \frac{dI_L(t)}{dt} \, dt = \frac{1}{2} \int_{t_2}^{t_3} V_2(t) \, dt - \frac{1}{2} \int_{t_2}^{t_3} V_i(t) \, dt \]

\[ W_L = \frac{1}{2} L \frac{dI_L}{dt} |_{t_3}^{t_2} = V_2 I_L |_{t_3}^{t_2} \]

4.3.4. Efficiency vs. switching frequency

Add up all of the energies lost during the switching transitions of one switching period:
\[ W_{\text{tot}} = W_{\text{on}} + W_{\text{off}} + W_D + W_C + W_L + \ldots \]

Average switching power loss is
\[ P_{\text{sw}} = \frac{W_{\text{tot}}}{f_s} \]

Total converter loss can be expressed as
\[ P_{\text{loss}} = P_{\text{con}} + P_{\text{fixed}} + W_{\text{tot}} f_s \]

where
\[ P_{\text{fixed}} = \text{fixed losses (independent of load and } f_s) \]
\[ P_{\text{con}} = \text{conduction losses} \]

Efficiency vs. switching frequency

Switching losses are equal to the other converter losses at the critical frequency
\[ f_{\text{crit}} = \frac{P_{\text{con}} + P_{\text{fixed}}}{P_{\text{off}}} \]

This can be taken as a rough upper limit on the switching frequency of a practical converter. For \( f_s > f_{\text{crit}} \), the efficiency decreases rapidly with frequency.
Summary of chapter 4

1. How an SPST ideal switch can be realized using semiconductor devices depends on the polarity of the voltage which the devices must block in the off-state, and on the polarity of the current which the devices must conduct in the on-state.
2. Single-quadrant SPST switches can be realized using a single transistor or a single diode, depending on the relative polarities of the off-state voltage and on-state current.
3. Two-quadrant SPST switches can be realized using a transistor and diode, connected in series (bidirectional-voltage) or in anti-parallel (bidirectional-current). Several four-quadrant schemes are also listed here.
4. A “synchronous rectifier” is a MOSFET connected to conduct reverse current, with gate drive control as necessary. This device can be used where a diode would otherwise be required. If a MOSFET with sufficiently low $R_{on}$ is used, reduced conduction loss is obtained.

5. Majority carrier devices, including the MOSFET and Schottky diode, exhibit very fast switching times, controlled essentially by the charging of the device capacitances. However, the forward voltage drops of these devices increases quickly with increasing breakdown voltage.
6. Minority carrier devices, including the BJT, IGBT, and thyristor family, can exhibit high breakdown voltages with relatively low forward voltage drop. However, the switching times of these devices are longer, and are controlled by the times needed to insert or remove stored minority charge.
7. Energy is lost during switching transitions, due to a variety of mechanisms. The resulting average power loss, or switching loss, is equal to this energy loss multiplied by the switching frequency. Switching loss imposes an upper limit on the switching frequencies of practical converters.
8. The diode and inductor present a “clamped inductive load” to the transistor. When a transistor drives such a load, it experiences high instantaneous power loss during the switching transitions. An example where this leads to significant switching loss is the IGBT and the “current tail” observed during its turn-off transition.
9. Other significant sources of switching loss include diode stored charge and energy stored in certain parasitic capacitances and inductances. Parasitic ringing also indicates the presence of switching loss.