ECE 325 – Electric Energy System Components
8- Fundamental Elements of Power Electronics

Instructor:
Kai Sun
Fall 2018
Content

(Selected materials from Chapter 21)

• Power semiconductor switches
  – Diodes, thyristors and controllable switches.

• Principles of AC-to-DC, DC-to-DC and DC-to-AC converters
Introduction

• A power electronics system is to process and control the flow of electric energy by supplying voltages and currents in a form that optimally suits the loads

• A typical power electronics (PE) system:
Applications of PE converters

• For **DC voltage/current**, a PE converter can regulate and adjust the **magnitude** to a desired level
• For **AC voltage/current**, a PE converter can adjust the **magnitude** and **frequency** and change the **number of phases**

• Applications:
  – Switched-mode (DC) power supplies
  – Uninterrupted power supplies (UPS)
  – Adjustable speed motor drives
  – High-voltage DC transmission (HVDC)
  – Battery-based utility energy storage
  – Electric vehicles (EVs) and hybrid electric vehicles (HEVs)
  – Renewable energy integration, e.g. solar PV and wind generation
## Classification of PE converters

<table>
<thead>
<tr>
<th>Four types of PE converters</th>
<th>Examples of application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AC-to-DC (rectifier)</strong></td>
<td>The battery (charging) interface to the power grid and power adapters for electronic devices</td>
</tr>
<tr>
<td><strong>DC-to-DC (boost up/step down)</strong></td>
<td>Power supplies for electronic devices</td>
</tr>
<tr>
<td><strong>DC-to-AC (inverter, to 1-phase or 3-phase AC)</strong></td>
<td>The battery (discharging) and solar PV interfaces to the power grid</td>
</tr>
<tr>
<td><strong>AC-to-AC</strong></td>
<td>Variable-speed motor drive</td>
</tr>
</tbody>
</table>

- **Examples of variable-speed motor drives (AC-to-AC converters)**

**Figure 23.3**
Variable-speed synchronous motor drive using a controlled rectifier and a line-commutated inverter fed from a dc link current source (see Section 23.2).

**Figure 23.5**
Variable-speed drive using a controlled rectifier and a self-commutated inverter fed from a dc link current source (see Section 23.9).
Power semiconductor switches

- They are key functional components in a PE converter besides resistors, inductors and capacitors.
- Two states: ON (conducting) and OFF (open-circuit)
- Three types in terms of the controllability
  - Not receiving control signal, e.g.
    - **Diode**: ON and OFF states controlled by the polarity and magnitude of voltage and the magnitude of current.
  - Partially controlled by a control signal, e.g.
    - **Thyristor**: turned ON by a control signal and OFF when current goes to zero
  - Controllable switch, e.g.
    - **GTO, IGBT, BJT, MOSFET**: both ON and OFF states are controllable by control signals
Ideal and Practical Diodes

- 2 terminals: A (anode) and K (cathode)
- **Rule 1**: OFF when $E_{AK}=0$
- **Rule 2**: OFF when $E_{AK}<0$ (reverse biased)
- **Rule 3**: ON (short-circuited) when $E_{AK}>0$ (forward biased)
- **Rule 4**: OFF when $I$ becomes 0
- Both ON and OFF switches are instantaneous

### Ideal I-V characteristics

- **ON**
- **OFF**

### Practical Diode:

- Turns ON when forward biased with a voltage $V_d$ about 0.7V or more, and it has a negligible voltage drop <1.5V.
- When it is OFF (reverse biased), it has a negligible current $I_S$ flowing through.
- At very large reverse bias beyond its peak inverse voltage ($V_{br}=50$ to 4000V), it is usually damaged and begins to conduct in reverse.
Thyristors

- Usually referred to semiconductor/silicon controlled rectifier (SCR)
- 3 terminals: A (anode), K (cathode) and G (gate)
- A thyristor behaves like a diode except that the instant of conduction can be controlled by “G”; that enables converting DC to AC
- Two conditions to conduct
  1. $E_{AK}>0$
  2. Positive current $I_g$ flows into “G” for at least a few microseconds
- Once conduction starts, “G” will lose control and conduction will continue until the current $I_A$ into “A” falls to zero
- If “G” and “K” are short-circuited, the thyristor is blocked
- A thyristor is partially controllable

Ideal I-V characteristics

Real I-V characteristics
Principles of gate firing

- We can control the current in an AC circuit by delaying the gate (G) pulses with respect to the start of each positive half-cycle.
  - If the pulses occur at the very beginning of each half-cycle, conduction lasts for 180° like a diode
  - If the pulses are delayed by \( \theta \), current only flows during the remaining 180°-\( \theta \)
Controllable power semi-conductor switches

• **Examples:**
  – GTO (Gate-turn-off thyristor)
  – IGBT (Insulated gate bipolar transistor)
  – BJT (Bipolar junction transistor)
  – MOSFET (Metal-oxide-semiconductor field effect transistor)

• **Ideal switch**
  – Vanishingly small power required from the control signal to trigger the switch
  – Switch between ON and OFF instantaneously when triggered by the control signal
  – When OFF, block arbitrarily large forward and reverse voltages with zero current flow
  – When ON, conduct arbitrarily large currents with zero voltage drop
Controllable power semi-conductor switches (cont’d)

• **Real switches:**
  
  – Requiring control power for switches (the less control power the simpler the control circuit)
  
  – Limited switching frequency

  – Having OFF-state leakage current
  
  – Having ON-state voltage (relevant to conducting losses)

  – Limited forward- & reverse-voltage blocking capability (the higher voltage blocking capability, the fewer switches in series)
  
  – Limited ON-state current rating (the higher current rating, the fewer switches in parallel)

  – Limited $dE/dt$ and $dI/dt$ ratings (requiring additional circuit to limit $|EI|$)
AC-to-DC converter: single-phase, diode bridge rectifier

**Figure 21.13**
b. Voltage levels.

d. Waveforms in load $R$. $E_d = 0.9E$.  

$E_m$
AC-to-DC converter: 3-phase, 6-pulse thyristor rectifier

- Control the DC output voltage $E_d$ by the delay angle $\alpha$ of triggering pulses

$$E_d = 1.35E \cos \alpha$$
Figure 21-40b
Delay angle: 15°.

Figure 21-40c
Delay angle: 45°.
Step-down DC-to-DC converter (buck chopper)

• To transfer power from a high-voltage DC source $E_S$ to a lower-voltage DC load $E_o$, one solution is to connect them by an inductor and to open and close the circuit periodically

− When switch closes, energy is transferred from $E_S$ to $E_o$ during time of closure $T_1$

$$E_S - E_o = L \frac{di}{dt}$$

Integration

$$i = \frac{E_S - E_o}{L} t$$

$$I_a \triangleq i(T_1) = \frac{E_S - E_o}{L} T_1$$

$$W = \frac{1}{2} LI_a^2$$

− When the switch opens, magnetic energy $W$ stored in the inductor is dissipated in the arc across the switch, so efficiency of power transfer is poor
1-Quadrant DC-to-DC converter

- Add an diode in order to deliver energy $W$ to load $E_o$ also when the switch opens:

$$L \frac{di}{dt} + E_o = 0 \quad \Rightarrow \quad i - I_a = -\frac{E_o}{L} t$$

If $i$ takes $T_2$ to become zero:

$$I_a = \frac{E_o}{L} T_2$$

$$I_a = \frac{E_S - E_o}{L} T_1$$

$$E_o T_2 = (E_S - E_o) T_1$$

$A- = A+$

(from previous slide)

- The inductor absorbs energy at a relatively high voltage $(E_S - E_o)$ and delivers it at a lower voltage $E_o$
- This circuit enables us to transfer energy without incurring any losses
- In reality, the mechanical switch is replaced by a controllable semi-conductor switch (GTO, MOSFET or IGBT).
Rapid switching

- Open and close the switch rapidly so that the current increases and decreases in a narrow range between $I_a$ and $I_b$
  - When the current falls to $I_b$ (after $T_b$), the switch recloses
  - When the current rises to $I_a$ (after $T_a$), the switch reopens

- Duty cycle:
  \[ D = \frac{T_a}{T_a + T_b} = \frac{T_a}{T} < 1 \]

- Average DC current to the load:
  \[ I_o = \frac{(I_a + I_b)}{2} \]

- Average DC current from the source:
  \[ I_s = I_o \frac{T_a}{T} = I_o D \ \Rightarrow \ I_o = I_s / D \]

- If there is no power loss
  \[ E_s I_s = E_o I_o = E_o I_s / D \ \Rightarrow \ E_o = DE_s \]

DC output voltage can simply be controlled by varying the duty cycle

- See Example 21-11
Impedance transformation

Duty cycle $D < 1$

$$I_o = I_s / D \quad E_o = D E_S$$

$$R_o = E_o / I_o$$

$$R_S = E_S / I_S = (E_o / D) / (I_o D)$$

$$= R_o / D^2$$

- The 1-quadrant DC-to-DC converter can transform the resistance of a fixed resistor to a higher value depending on $D$.
  - It behaves like a DC transformer whose turns ratio is $1/D$
  - Unlike a transformer, which allows power to flow bi-directionally, a step-down chopper can transfer power only from the high-voltage side to the low-voltage side

- See Example 21-12
Consider two mechanical switches S1 and S2 that open and close alternatively.
- Within the time of a cycle $T = T_a + T_b$, S1 is closed for $T_a$ and S2 is closed for $T_b$.
- S1 has duty cycle $D = T_a / T$ and S2 has duty cycle $T_b / T = (1 - D)$.
- Output voltage $E_{12}$ fluctuates between $E_H$ and 0, having the average DC output $E_L = DE_H$ (variable by varying $D$).

**2-quadrant converter:**
- **Specific voltage polarity**: Terminal 1 is always (+) with respect to terminal 2.
- **Bidirectional current**: current and power can flow from $E_H$ to $E_L$, or vice versa since current always circulate through either S1 or S2.
• Assume the load to be a battery $E_o$ with internal resistance $R$

• Use inductor $L$ as a buffer between the fluctuating $E_{12}$ and constant $E_o$

  Average current $I_L = (E_L - E_o)/R$

• If average DC voltage $E_L = E_o$, then $I_L = 0$ and no dc power exchange happens

• Step-down chopper (buck mode):
  - If $E_L > E_o$, power $= |E_L I_L|$ flows to $E_o$

• Step-up chopper (boost mode):
  - If $E_L < E_o$, power $= |E_L I_L|$ flows to $E_H$

• In reality, mechanical switches S1 and S2 are replaced by semi-conductor switches Q1 and Q2 each with a diode placed in antiparallel for bi-directional currents

• Q1 and Q2 cannot be closed at the same time to avoid a short-circuit across $E_H$; in each half cycle, they both open for a very brief dead time (zero current from $E_H$) for a safety margin

• See Example 21-13
Output voltage ripple filter

- A LC low-pass filter is applied to create almost flat DC output voltage $E_o$.
- Ripples only appear in $I_L$, not $I_o$.

$$
T = T_a + T_b
$$

![Diagram of four-quadrant dc-to-dc converter](image)

**Figure 21.73**
Four-quadrant dc-to-dc converter feeding a passive dc load $R$.

$$
f_{LC} = \frac{1}{2\pi\sqrt{LC}} \ll f = \frac{1}{T}
$$

$$
\Delta I_L = \frac{E_o}{L} T_b = \frac{E_o}{L} (1 - D) T
$$

$$
\Delta Q = \int I_c dt = \frac{1}{2} \frac{\Delta I_L T}{2} = \frac{\Delta I_L T}{8} = \frac{E_o}{8L} (1 - D) T^2
$$

$$
\frac{\Delta E_o}{E_o} = \frac{\Delta Q}{CE_o} = \frac{(1 - D) T^2}{8 LC} = \frac{\pi^2 (1 - D) \left( \frac{f_{LC}}{f} \right)^2}{2} \approx 0
$$
4-quadrant DC-to-DC converter

- It consists of two identical 2-quadrant converters having the same switching frequency, e.g. 100kHz

- **Switching rules:**
  - Q1 and Q2 on arm A open and close alternately
  - Q3 and Q4 on arm B open and close alternately
  - Q1 and Q4 open and close simultaneously (duty cycle $D$)
  - Q2 and Q3 open and close simultaneously (duty cycle $1-D$)

- **4-quadrant:**
  - $E_{LL}$ changes between $-E_H$ and $+E_H$
  - The DC current flow of the load between A and B is bidirectional

![Diagrams showing the operation of the 4-quadrant DC-to-DC converter](image)

$$E_{A2} = DE_H \quad E_{B2} = (1-D)E_H$$

$$E_{LL} = E_{A2} - E_{B2} = (2D-1)E_H$$

**Figure 21.71** Voltage output when $D = 0.5$. The average voltage is zero.

**Figure 21.72** Voltage output when $D = 0.8$. The average voltage $E_{LL}$ is $0.6 E_H$. 

22
**DC-to-AC rectangular wave converter**

- The 4-quadrant converter with $D=0.5$ is able to transform a DC voltage $E_H$ into a rectangular AC voltage $\pm E_H$, which contains a fundamental sinusoidal component having an amplitude of $1.27E_H$ and an effective value of $1.27E_H/\sqrt{2}=0.90E_H$

- It is bidirectional (DC-to-AC and AC-to-DC) and frequency-variable

- The output has a fixed amplitude and large $3^{rd}$, $5^{th}$ and $7^{th}$ harmonics.

$$E_{LL} = \frac{400}{\pi} \left[ \sin(2\pi ft) + \frac{1}{3}\sin(6\pi ft) + \frac{1}{5}\sin(10\pi ft) + \ldots \right]$$
PWM (pulse width modulation)

- 4-quadrant DC-to-DC converter using a carrier frequency $f_c$ and different values of $D$

$$E_{LL} = (2D-1)E_H$$

- To obtain $E_{LL}(t) = E_m \sin(2\pi ft + \theta)$,

$$D(t) = \frac{E_m}{2E_H} \sin(2\pi ft + \theta) + \frac{1}{2}$$
DC-to-AC sine wave converter with Bipolar/Unipolar PWM

- Once the carrier frequency is filtered out, the resulting voltage will be sinusoidal.
- A higher carrier frequency would yield a better sinusoidal waveform but would increase the power losses of the electronic switches, e.g. IGBTs.

Figure 21.83
Alternative (+) and (−) pulses contain the sinusoidal component.

Figure 21.84
Sequential (+) and (−) pulses contain the sinusoidal components.
DC-to-AC non-sine wave converters with PWM

- With $D$ varying periodically between 0.8 and 0.2 at a frequency $f < 0.1f_c$
- Although $f_c$ is fixed, the ON/OFF pulse widths change continually with $D$.
- That is why this type of switching is called **Pulse Width Modulation (PWM)**