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

Instructor:
Kai Sun
Fall 2015
Content

(Materials are from Chapter 21)

• Power semiconductor switches
  – Diodes, thyristors, etc.

• DC-to-DC switching converters

• DC-to-AC switching 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 or current, a PE converter can regulate the magnitude at a desired level or adjust the magnitude to a desired level.
- For AC voltage or 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>DC-to-DC (boost up/step down):</td>
<td>Power supplies for electronic devices</td>
</tr>
<tr>
<td>DC-to-AC (inverter, to 1-phase or 3-phase AC)</td>
<td>The battery (discharging) and solar PV interfaces to the power grid</td>
</tr>
<tr>
<td>AC-to-DC (rectifier)</td>
<td>The battery (charging) interface to the power grid and power adapters for electronic devices</td>
</tr>
<tr>
<td>AC-to-AC</td>
<td>Variable-speed motor drive</td>
</tr>
</tbody>
</table>

- Two examples of AC-to-AC convertors:

![Figure 23.1](image1.png)  
*Figure 23.1*  
Variable-speed drive system using a cycloconverter (see Sections 23.3 and 23.5).

![Figure 23.6](image2.png)  
*Figure 23.6*  
Variable-speed drive using a controlled rectifier and a self-commutated inverter fed from a dc link voltage source (see Section 23.10).
Power semiconductor switches

• Power semiconductor switches are the key functional components in a PE converter; other components are such as resistors, inductors and capacitors.
• Two states: ON (conducting) and OFF (open-circuit)
• Three types of power semiconductor devices in terms of the controllability
  – **Diodes**: their ON and OFF states are controlled by the polarity and magnitude of its voltage and the magnitude of its current.
  – **Thyristors**: they are turned ON by a control signal and turned OFF when its current goes to zero
  – **Controllable switches**: both ON and OFF states are controllable by control signals
Ideal Diode

• 2 terminals: A (anode) and K (cathode)
• It starts to conduct (ON) as long as the voltage $E_{AK}$ is forward biased
• When ON, it has no voltage drop
• It turns OFF and has no leakage current when $E_{AK}$ is reverse biased
• Both turn ON and OFF switches are instantaneous

Ideal I-V characteristics

Figure 21.9
Basic rules governing diode behavior.
Practical Diodes

• When a diode is **forward biased** with a voltage about 0.7V or more is applied, it acts like a closed switch with a negligible voltage drop <1.5V.

• When a diode is **reverse biased**, it has a negligible current flowing through.

• At very large reverse bias, beyond its peak inverse voltage (PIV, 50V-4000V), the diode breaks down, begins to conduct in reverse and is usually damaged.
Thyristors

• Usually referred to semiconductor 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
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

• With reverse voltage blocking capability
  – GTO (Gate-turn-off thyristor)
  – IGBT (Insulated gate bipolar transistor)

• Without reverse voltage blocking capability
  – BJT (Bipolar junction transistor)
  – MOSFET (Metal-oxide-semiconductor field effect transistor)
Ideal switch

- Switch from ON to OFF, or vice versa, instantaneously when triggered by the control signal.
- Vanishingly small power required from the control signal to trigger the switch.
- When OFF, block arbitrarily large forward and reverse voltages with zero current flow.
- When ON, conduct arbitrarily large currents with zero voltage drop.
**Real switches**

- Have OFF-state leakage current
- Have ON-state voltage (relevant to conducting losses)
- Limited switching frequency
- Limited forward- and reverse-voltage blocking capability
  - Fewer switches in series are needed with a higher voltage blocking capability
- Limited ON-state current rating
  - Fewer switches in parallel are needed with a higher ON-state current rating
- Control power is required for switches
  - The control circuit can be simplified with less control power
- Limited $dE/dt$ and $dI/dt$ ratings
  - Need additional circuit to limit $|EI|$
Step-down DC-to-DC converter (buck chopper)

- The voltage step-up/step-down in AC systems can easily be done with a transformer, but in DC systems, a DC-to-DC switching converter is required using a different approach.

- 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 close, energy is transferred from $E_S$ to $E_o$ during time of closure $T_1$

    \[ E_S - E_o = L \frac{di}{dt} \quad \Rightarrow \quad i = \frac{E_S - E_o}{L} t \]

    \[ i(T_1) = \frac{E_S - E_o}{L} T_1 = I_a \]

    \[ W = \frac{1}{2} LI_a^2 \]

  - When the switch opens, energy $W$ stored in the inductor is dissipated in the arc across the switch, so efficiency of power transfer is poor.

\[ (E_S - E_o) \]
• To deliver energy $W$ to load $E_o$ when the switch opens, add an diode

\[ L \frac{di}{dt} + E_o = 0 \quad \rightarrow \quad i - I_a = -\frac{E_o}{L} t \]

If $i$ takes $T_2$ to become zero

\[ I_a = \frac{E_s - E_o}{L} T_1 \]

\[ I_a = \frac{E_o}{L} T_2 \quad \rightarrow \quad E_o T_2 = (E_s - E_o) T_1 \]

\[ A_+ = A_- \]

\[ \frac{T_2}{T_1} = \frac{E_s - E_o}{E_o} \]

- 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
- The switch is actually a GTO, MOSFET or IGBT, whose ON/OFF state is controlled by a signal applied to the gate.
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 reaches $I_a$ (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:
  $$I_s = I_o \left(\frac{T_a}{T}\right) = I_o D \quad \Rightarrow \quad I_o = I_s / D$$

- If there is no power loss
  $$E_s I_s = E_o I_o = E_o I_s / D \quad \Rightarrow \quad E_o = D E_s$$

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

Figure 21.60a
Currents in a chopper circuit.

$$I_a - I_b = \frac{E_s - E_o}{L} T_a = \frac{E_o}{L} T_b$$

Figure 21.60b
Current in the load.

Figure 21.60c
Current pulses provided by the source.
Impedance transformation

Duty cycle $D < 1$

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

$R_o = E_o / I_o$

$R_S = E_S / I_S = (E_o / D) / (I_o D) = R_o / D^2$

A step-down DC-to-DC converter (chopper) 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 $D$
- Unlike a transformer allowing power to flow bi-directionally, a step-down chopper can transfer power only from the high-voltage side to the low-voltage side
Basic 2-quadrant DC-to-DC converter

- 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 $E_L = D E_H$ (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 $R$, and 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
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 connected between A and B can be from A to B or from B to A

\[
E_{A2} = DE_H \\
E_{B2} = (1-D)E_H \\
E_{LL} = E_{A2} - E_{B2} = (2D-1)E_H
\]
\[ E_{LL} = E_{A2} - E_{B2} = (2D - 1)E_H \]

**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 \( E_H \).
Output voltage ripple filter

- A LC low-pass filter is applied to create almost flat DC output voltage $E_o$
- $f_{LC} < f = 1/T$

\[ T = T_a + T_b \]

\[ T_a, T_b \]

\[ \Delta I_L \]

\[ I_L, I_o \]

\[ \Delta Q \]

\[ E_L, E_o \]

\[ E_H, -E_o \]

\[ I_L, I_c, E_o \]

\[ T^2 \]

\[ \Delta E_o \]

\[ \frac{\Delta E_o}{E_o} = \frac{(1-D)T^2}{8LC} = \frac{\pi^2 (1-D)}{2} \left( \frac{f_{LC}}{f} \right)^2 \approx 0 \]
Examples 21-11, 21-12, 21-13
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 3rd, 5th and 7th harmonics.
DC-to-AC converter with PWM (pulse width modulation)

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

\[ E_{LL} = (2D-1)E_H \]

\[ E(t) = E_m \sin(2\pi ft + \theta) \]

\[ D(t) = \frac{E_m}{2E_H} \sin(2\pi ft + \theta) + \frac{1}{2} \]
Two DC-to-AC non-sine wave converters with PWM

- With $D$ varying periodically between 0.8 and 0.2 at a frequency $f < 0.1 f_c$
- 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* or PWM
DC-to-AC sine wave converter with PMW

- To obtain $E_{LL}(t) = E_m \sin(2\pi f t + \theta)$
  
  $$D(t) = \frac{E_m}{2E_H} \sin(2\pi ft + \theta) + \frac{1}{2}$$

Amplitude modulation ratio $m = \frac{E_m}{E_H}$
Frequency modulation ratio $m_f = \frac{f_c}{f}$

- Create a 83.33Hz sine voltage wave with a 100V peak value using a DC-to-AC converter with $E_H=200V$ and $f_c=1000$Hz:

  $T = \frac{1}{83.33} = 0.012s = 12000\mu s$

  $T_c = \frac{1}{1000} = 1000\mu s$

  $T/T_c = 12$, so each $T_c$ covers $360/12 = 30^\circ$

  Calculate $D$ for $\phi(t) = 2\pi ft + \theta = 0^\circ, 30^\circ, 60^\circ, \ldots$, which correspond to $E_{LL} = 100\sin\phi$ (V)

  In each carrier period $T_c$, Q1&Q4 are ON for first $DT_c = 1000D(\mu s)$ and then Q2&Q3 are ON for the remaining $(1-D)T_c = 1000(1-D)$ ($\mu s$)
Bipolar PWM and 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.

- 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.
Creating the PMW pulse train

Switch Q1 is ON (Q2 is OFF) whenever $E_L$ is above the triangular wave

**Figure 21.87**
A comparator determines the crossing points between the miniature version $E_S$ of the wanted waveshape $E_{L(t)}$ and a triangular waveshape, thereby producing the control signal $D_{(t)}$. The signal triggers the switches in the chopper to generate the PWM waveshape that contains the wanted output $E_{L(t)}$.

**Figure 21.86**
a. Transforming a desired voltage $E_{L(t)}$ into a series of PWM pulses using a two-quadrant chopper.
b. Pulse-width modulated form of the original $E_{L(t)}$ waveshape.
DC-to-AC 3-phase converter

- Switch Q1 is ON (Q2 is OFF) whenever $E_{AY}$ is above the triangular wave
- Switch Q3 is ON (Q4 is OFF) whenever $E_{BY}$ is above the triangular wave
- Switch Q5 is ON (Q6 is OFF) whenever $E_{CY}$ is above the triangular wave

Figure 21.93
Block diagram of a 3-phase PWM converter.
Figure 21.88
Three-phase PWM voltages produced by a dc-to-ac switching converter operating at 540 Hz with a 500 V dc input. Top: $E_{AN}$, $E_{BN}$, $E_{CN}$ outputs, peak 60 Hz sinusoidal component = 200 V. Bottom: $E_{AB}$, $E_{BC}$, $E_{CA}$ outputs, peak 60 Hz sinusoidal component = 346.4 V, rms value = 245 V.
3-phase, 6-pulse thyristor rectifier (AC-to-DC converter)

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

$$E_d = 1.35E \cos \alpha$$
Homework Assignment #7

• Read Chapters 17 and 21
• Questions:
• Due date:
  – hand in your solution to Denis at MK 205 or by email (dosipov@vols.utk.edu) before the end of 11/30 (Monday)