Introduction to Power Electronics

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Chapter 1

Introduction of Power Electronics

• What is Power Electronics?
• Power Conversion and Basic Principle
• Switching Power Devices in General
• Diode, Thyristor and Power Transistor
• Power MOSFET and IGBT
• GTO and MCT
• Power IC
What is Power Electronics?

Power Electronics is power conversion and control from one form of power (energy) source to a desired form by using electronic means. Example: An electric vehicle drive must convert dc input to ac output that has variable voltage and variable frequency.

Power electronics is power processing circuits and control.
What is Power Electronics? Cont.

Power Processor (PE Circuits)

Raw power in
- Battery
- Fuel Cell
- Utility
- Solar
- Wind
- Capacitor/Inductor
- Dc or ac

Desired power out (V, I, P, F)

To loads:
- Motor
- Utility line
- Computer
- Equipment
- Process

Control
Multi-disciplinary Nature of Power Electronics

- Circuit theory
- Systems & Control theory
- Comm. & Signal processing
- Electronics DSP, FPGA
- Simulation & computing
- Power systems
- Electromagnetics EMI
- Solid-state physics
- Electric machine
- Power systems
- Electromagnetics EMI
- DSP Control Board
Principle of Power Control Using Switch

- Current Control Using Variable Resistor

- Current Control Using Switching Device
Category of Power Conversion

- AC-DC Converter (Rectifier)
- AC-AC Converter (Power Controller, Cycloconverter, Matrix converter)
- DC-AC Converter (Inverter)
- DC-DC Converter (DC Chopper - Buck/Boost/Buck-Boost Converter)
Principle of AC-DC Converter (Rectifier)

$V_1$ - AC Source
$V_2$ - DC Load

Waveforms of AC-DC Converter
Principle of AC-AC Converter

(AC Power Controller)

\[ V_1 - \text{AC Source} \]
\[ V_2 - \text{AC Load} \]
\[ S - \text{AC Switch} \]

Waveforms of AC Power Adjuster
Principle of AC-AC Converter

(Cycloconverter or Frequency Changer)

$V_1$ - AC Source
$V_2$ - AC Load
$S$ - AC Switch

Waveforms of Cycloconverter

$S_1$, $S_4$ - ON
$S_2$, $S_3$ - OFF

Fundamental
Principle of DC-AC Converter (Inverter)

Voltage-Source Inverter

Waveforms of Inverter
Why Switching?

Power Loss: \( \left( \frac{V_{dc}}{r + R_L} \right)^2 r \)

Power Consumption: \( \left( \frac{V_{dc}}{r + R_L} \right)^2 R_L \)

\[ P_{Loss} = V_{CE} I_C \]

\[ P_{ON} \]

\[ P_{OFF} \]
### Switching Devices

<table>
<thead>
<tr>
<th>Current</th>
<th>Uncontrollable</th>
<th>On - Controllable</th>
<th>On and Off Controllable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image" alt="Diode" /></td>
<td><img src="image" alt="Thyristor" /></td>
<td><img src="image" alt="Transistor" /></td>
</tr>
<tr>
<td>Uni-Direction</td>
<td></td>
<td></td>
<td>MOSFET*</td>
</tr>
<tr>
<td>Bi-Direction</td>
<td>Triac</td>
<td>Module</td>
<td>GTO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>IGBT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SIT, SITH, MCT, MTO, etc.</td>
</tr>
</tbody>
</table>

* Metal Oxide Semiconductor Field Effect Transistor
Diode and Rectifier

\[ v_{ac} \rightarrow v_o \rightarrow v \]

\[ v_{ac} \rightarrow i_L \rightarrow \omega t \]

\[ + \rightarrow i \rightarrow - \]

Load
Thyristor and Phase-Controlled Rectifier

\[ i_1, v \]

\[ i_G \]

\[ v_{ac} \]

\[ v_O \]

\[ \alpha \]

\[ \omega t \]

Load

\[ i_L \]

\[ v_O \]

\[ i_L \]

\[ \pi \]

\[ 2\pi \]

\[ I_{g3}, I_{g2}, I_{g1} = 0 \]

\[ I_{g2} > I_{g3} > I_{g1} \]
Power Transistor and Inverter

IGBT

Gate Drive Circuit of IGBT
Safe Operating Area and Snubber Circuit

Turn-off Waveform

SOA and Turn-off Trajectory

Traditional Snubber Circuits
IGBT Technology

Saturation Voltage $V_{ce}$ [V] vs. $t_f$ [us]

- 1st Gen. ('85)
- 2nd Gen. ('89)
- 3rd Gen. ('94)
- Further curve

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Progress of Large VA Rated GTO

Year

Turn-off Current [kA]

- 400V/5A 600V/200A
- 2.5kV/600A
- 2.5kV/2kA
- 4.5kV/2kA
- 5kV/2.5kA
- 4.5kV/3kA
- 5kV/2.5kA
- 6kV/2.5kA
- 4.5kV/2.7kA
- 6kV/3kA
- 6kV/6kA

'85 '75 '70 '80 '90 '95 '00
High-Voltage Power IC

- 220V/1A one-chip 3-phase inverter IC
- Smart power switching device module / Intelligent Power Module (IPM)
- Power Electronics Building Block (PEBB)
- etc.
Chapter 1

What We have Learned:

• What's Power Electronics
• How to use ideal switches to do power conversion
• How to model and analyze PE circuits (basic principle)
• Real switching devices (D, Thy, IGBT, MOSFET, GTO, IGCT, etc)
• Snubber circuits for safer operation
• Combinations of transistor(s) and diode(s) for
  – Bi-directional current and unidirectional voltage switches
  – Bi-directional current and bi-directional voltage switches (ac switch)
Chapter 2  Basic Circuits of
Power Conversion

Contents
• Natural (Line, Load) Commutated Converter, Rectifier, and Cycloconverter
• Self-commutated Converter
  – Voltage-Source (Voltage-Fed) Inverter
  – Current-Source (Voltage-Fed) Inverter
• DC Chopper and DC/DC Converter
• AC Switch: AC Power Adjusting and Matrix Converter
• Multilevel inverters
Diode rectifiers are the simplest power conversion circuit. They change ac to dc. The circuits are simple, however, the following points should be understood:

• how it works
• how to smooth voltage/current to get a decent dc voltage/current
• how to determine the output voltage from the input voltage
Diode Rectifier (Cnt’d)

With Free-Wheeling Diode

Full Bridge Rectifier

\[ V_S, L_F, V_L, R, V_R \]
Diode Rectifier (Cnt’d)

$V_S$  $V_{DC}$  $V_{Sab}$  $V_{Sbc}$  $V_{Sca}$

Diagram showing a diode rectifier circuit with labeled voltages.

$V_{DC}$  $V_R$
Diode Rectifier (Cnt’d)

- $V_S$
- $i_{Sa}$
- $v_{Sa}$
- $V_{DC}$
- $V_{Sab}$
- $V_{Sbc}$
- $V_{Sca}$
- $V_{DC}$
Natural Commutated Converter

- phase-controlled rectifier (1 phase) -
Natural Commutated Converter

- phase controlled rectifier (3 phase) -
Self-Commutated Power Converter

- voltage-source inverter -

Single Phase Full Bridge Inverter and Freewheeling Diode or Antiparallel Diode

Rec. Mode

Inv. Mode

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Dual Relationship of PE Circuits

- Voltage-source
- Voltage
- Current
- Parallel connection
- Series connection
- Inductive component
- Capacitive component
- Switch open
- Switch close
- Line-to-line voltage

- Current-source
- Current
- Voltage
- Series connection
- Parallel connection
- Capacitive component
- Inductive component
- Switch close
- Switch open
- Line /or phase current
• 70% electricity is used by motors. Energy saving and control are essential to many applications.
Voltage-Source Inverter (6-step)

\[ Va = \frac{(Gap - Gan)}{2} E \]
\[ Vb = \frac{(Gbp - Gbn)}{2} E \]
\[ Vc = \frac{(Gcp - Gcn)}{2} E \]
Voltage-Source Inverter (PWM)

\[
\begin{align*}
V_a &= \left(\text{Gap} - \text{Gan}\right)E/2 \\
V_b &= \left(\text{Gbp} - \text{Gbn}\right)E/2 \\
V_c &= \left(\text{Gcp} - \text{Gcn}\right)E/2
\end{align*}
\]
DC/DC Converter  a) Buck Converter

i) Circuit

ii) S on

iii) S off

iv) waveforms

gate of S

ein

current

Eout = 0 ~ Ein
DC/DC Converter  b) Boost Converter

\[ E_{\text{out}} = E_{\text{in}} - \Delta E \]
DC/DC Converter  
c) Buck/Boost Converter

\[
\begin{align*}
E_{in} & \rightarrow S & D & \rightarrow E_{out} \\
L & \rightarrow D & C & \rightarrow E_{out} \\
C & \rightarrow D & E_{out} \\
E_{out} & = 0 \rightarrow \infty
\end{align*}
\]
DC/DC Converter

a) Buck Converter

i) Circuit

ii) S on

iii) S off

iv) waveforms

gate of S

current

voltage

Eout = 0 ~ Ein

b) Boost Converter

i) Circuit

ii) S on

iii) S off

iv) waveforms

gate of S

current

voltage

Eout = Ein ~ 0

c) Buck/Boost

i) Circuit

ii) S on

iii) S off

iv) waveforms

gate of S

current

voltage

Eout = 0 ~ CD
AC Switches: AC Power Regulator

Load

\[ v_1 \rightarrow S \rightarrow \text{Load} \rightarrow v_2 \]
AC Switches: Matrix Converter

3-Phase Load or Motor