ELECTRONICS POWER CONVERSION

INTRODUCTION

• Definition and concepts of Electronics Power Conversion
• Application
• Power semiconductor switches
• Gate/base drivers
• Losses
• Snubbers
• Links to useful websites
• Reading material:
  – Mohan (Chapter)
  – Bose paper
ELECTRONIC POWER CONVERSION

• DEFINITION: To convert, i.e. to process and control the flow of electric power by supplying voltage s and currents in a form that is optimally suited for user loads.

• More popularly known as “power electronics” (PE) systems. Basic block diagram shown in Figure 1.
Goal of electronic power conversion systems

- To convert electrical energy from one form to another, from the source to load with highest efficiency, high availability and high reliability with the lowest cost, smallest size and weight.

- Static and applications
  - involves non-rotating or moving mechanical components.
  - E.g. rectifiers, inverters, choppers, cycloconverters.

- Drive applications
  - intimately contains moving or rotating components such as motors.
  - E.g. DC drives, AC drives, Permanent magnet motor drives.
Conversion concept: example

- Supply from TNB: 50Hz, 240V RMS (340V peak). Customer need DC voltage for welding purpose, say.

- TNB sine-wave supply gives zero DC component!

- We can use simple half-wave rectifier. A fixed DC voltage is now obtained. This is a simple PE system.

Average output voltage: $V_o$

$$V_o = \frac{V_m}{\pi}$$
Concept-cont’d

How if customer wants variable DC voltage? More complex circuit using SCR is required.

Average output voltage:

\[ V_o = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin(\omega t) d\omega t = \frac{V_m}{2\pi} [1 + \cos \alpha] \]

By controlling the firing angle, \( \alpha \), the output DC voltage (after conversion) can be varied.

Obviously this needs a complicated electronic system to set the firing current pulses for the SCR.
Applications

• Power generation and transmission (HVDC)
• Uninterruptable power supplies (UPS)
• DC power supplies
• Energy conservation (ballast, pumps, compressors, air-condition)
• Transportation (Electric car, trains)
• Process control and factory automation
• Electroplating, Welding
• Heating, cooling
• Utility-related application
Current issues related to power electronics: Energy scenario

- Energy Scenario.
  - Need to reduce dependence on fossil fuel (coal, natural gas, oil) and nuclear power resource (uranium).
  - Depletion of these sources is expected (see Bose paper).
  - Effort to tap renewable energy resources such as solar, wind, fuel-cell etc. need to be increased.
  - Energy saving: 15-20% of electricity can be saved by PE applications.
  - E.g. variable speed drives (air conditioned, fans, pumps). Variable speed compressor aircond system saves up to 30% of energy compared to conventional thermostat-controlled system.
  - electrical lighting using electronics ballast can boost the efficiency of fluorescent lamp by 20%.
Environmental issues

- Environment issues
  - Nuclear safety. Nuclear plants can remain radioactive for thousands of years.

  - Burning of fossil fuel emits gases such as $\text{CO}_2$, CO (oil burning), $\text{SO}_2$, $\text{NO}_x$ (coal burning) etc.

  - Creates global warming (green house effect), acid rain and urban pollution from smokes.

  - One way to reduce the problem is to promote renewable energy resources.

  - To mitigate the pollution problem, centralization of power stations to remote non-urban areas needed. Stringent controls can be imposed on central power plants.

  - Special effort is needed to reduce pollution in cities by enforcing the use of electric vehicle.
PE growth

• PE rapid growth due to:
  – Advances in power (semiconductor) switches
  – Advances in microelectronics (DSP, VLSI, microprocessor/microcontroller, ASIC)
  – New ideas in control algorithms
  – Demand for new applications

• PE is an interdisciplinary field:
  – Digital/analogue electronics
  – Power and energy
  – Microelectronics
  – Control system
  – Computer, simulation and software
  – Solid-state physics and devices
  – Packaging
  – Heat transfer
Power Electronics Converters

AC to DC: RECTIFIER

DC to DC: CHOPPER

DC to AC: INVERTER
Application example: Static converter

DC to DC converter

Switched-mode power supply

MEE 1413: Electronics
Power Conversion  Dr.
Zainal Salam; Dec 2000
Application example: Variable speed drive system

![Diagram of Variable speed drive system]

- **Power Source**
- **Controller**
- **Power Electronics Converter**
- **Motor**
- **Process/Load**
- **Process Control Computer**

**Diagram of Air-conditioning system**

- **Power Source**
- **Variable speed drive**
- **Power Electronics Converter**
- **Motor**
- **Air conditioner**
- **Building Cooling**
- **Indoor temperature and humidity**
- **Indoor sensors**
- **Desired temperature**
- **Desired humidity**
Power semiconductor devices
(Power switches)

• Power switches are the work-horses of PE systems.

• PE switches works in two states only:
  – Fully on (conducting);
  – Fully off (blocking)

• Can be categorised into three group
  – Diode : on and off states controlled by power circuit only

  – Thyristor (SCR) : Latched on by low-power control signal but must be turned off by power circuit. Cannot be turned off by control signal.

  – Controllable switches: Can be turned on and off by low-power control signals (e.g. BJT, MOSFET, IGBT, GTO)
Power Diode

- When diode is forward biased, it conducts current with a small forward voltage ($V_f$) across it (0.2-3V)

- When reversed (or blocking state), a negligibly small leakage current (uA to mA) flows until the reverse breakdown occurs. Diode should not be operated at reverse voltage greater than $V_r$
Reverse Recovery

- When a diode is switched quickly from forward to reverse bias, it continues to conduct due to the minority carriers which remains in the p-n junction.

- The minority carriers require finite time, i.e, $t_{rr}$ (reverse recovery time) to recombine with opposite charge and neutralise.

- Effects of reverse recovery are increase in switching losses, increase in voltage rating, over-voltage (spikes) in inductive loads.
Softness factor, $S_r$

Snap-off

$$S_r = \frac{(t_2 - t_1)}{(t_1 - t_0)}$$

$$= 0.3$$

Soft-recovery

$$S_r = \frac{(t_2 - t_1)}{(t_1 - t_0)}$$

$$= 0.8$$
Types of Power Diodes

• Line frequency (general purpose):
  – on state voltage very low (below 1V)
  – large $t_{rr}$ (about 25us)
  – very high current (up to 5kA) and voltage (5kV) ratings
  – Used in line-frequency (50/60Hz) applications such as rectifiers

• Fast recovery
  – very low $t_{rr}$ (<1us).
  – Power levels at several hundred volts and several hundred amps
  – Normally used in high frequency circuits

• Schottky
  – very low forward voltage drop (typical 0.3V)
  – limited blocking voltage (50-100V)
  – Used in low voltage, high current application such as switched mode power supplies.
Thyristor (SCR)

- Thyristors can only be turned on with two conditions:
  - the device is in forward blocking state (i.e. $V_{ak}$ is positive)
  - a positive gate current ($I_g$) is applied at the gate

- Once conducting, the anode current is LATCHED (continuously flowing).
Turning on/off mechanism

• In reverse-biased mode, the SCR behaves like a diode. It conducts a small leakage current which is almost dependent of the voltage, but increases with temperature.

• When the peak reverse voltage is exceeded, avalanche breakdown occurs, and the large current will flow.

• In the forward biased mode, with no gate current present (i.e. in the untriggered state, the device exhibits a leakage current.

• If the forward breakover voltage (Vbo) is exceeded, the SCR “self-triggers” into the conducting state and the voltage collapses to the normal forward volt-drop, typically 1.5-3V. The presence of any gate current will reduce the forward breakover voltage.
Thyristor Conduction

- Thyristor cannot be turned off by applying negative gate current. It can only be turned off if $I_a$ goes negative (reverse)
  - This happens when negative portion of the sine-wave occurs (natural commutation),

- Another method of turning off is known as “forced commutation”,
  - The anode current is “diverted” to another circuitry.
Types of thyristors

• Phase controlled
  – rectifying line frequency voltage and current for ac and dc motor drives
  – large voltage (up to 7kV) and current (up to 4kA) capability
  – low on-state voltage drop (1.5 to 3V)

• Inverter grade
  – used in inverter and chopper

• Light activated
  – Similar to phase controlled, but triggered by pulse of light.
  – Normally very high power ratings

• TRIAC
  – Dual polarity thyristors
Controllable switches (power transistors)

- Can be turned “ON” and “OFF” by relatively very small control signals.

- Operated in SATURATION and CUT-OFF modes only. No “linear region” operation is allowed due to excessive power loss.

- In general, power transistors do not operate in latched mode.

- *Traditional devices:* Bipolar junction transistors (BJT), Metal oxide silicon field effect transistor (MOSFET), Insulated gate bipolar transistors (IGBT), Gate turn-off thyristors (GTO)

- *Emerging (new) devices:* Gate controlled thyristors (GCT).
Bipolar Junction Transistor (BJT)

- Ratings: Voltage: $V_{CE} < 1000$, Current: $I_C < 400\, \text{A}$. Switching frequency up to 5kHz. Low on-state voltage: $V_{CE(sat)} : 2-3\, \text{V}$

- Low current gain ($\beta$). Need high base current to obtain reasonable $I_C$. Expensive and complex base drive circuit.

- Not popular in new products.
BJT characteristics

• To turn on/off the device, a base drive circuit is connected to the base and emitter terminal.

• To turn on, current is injected into the base terminal. When turned on, conventional current passes from collector to emitter.

• To turn-off, the base current is removed.

• The current gain of a BJT ends to be low when operated in the saturated ON condition. $\beta < 10$ is common. It deteriorates as voltage ratings increases.

• It is normal to use Darlington connection for higher current gain.
**BJT Darlington pair**

\[ \beta = \frac{I_c}{I_{B1}} = \frac{(I_{c1} + I_{c2})}{I_{B1}} = \frac{I_{c1}}{I_{B1}} + \frac{I_{c2}}{I_{B1}} \]

\[ = \beta_1 + \left( \frac{I_{c2}}{I_{B2}} \right) \cdot \left( \frac{I_{B2}}{I_{B1}} \right) = \beta_1 + \beta_2 \cdot \left( \frac{I_{B1} + I_{c1}}{I_{B1}} \right) \]

\[ = \beta_1 + \beta_2 \cdot (1 + \beta_1) \]

\[ \Rightarrow \beta = \beta_1 + \beta_2 + \beta_1 \beta_2 \]
Metal Oxide Silicon Field Effect Transistor (MOSFET)

- Ratings: Voltage $V_{DS} < 500V$, current $I_{DS} < 300A$.

- Very fast device: $>100$KHz. For some low power devices (few hundred watts) may go up to MHz range.
MOSFET characteristics

- Turning on and off is very simple. Only need to provide $V_{GS} = +15\text{V}$ to turn on and $0\text{V}$ to turn off. Gate drive circuit is simple.

- Basically low voltage device. High voltage device are available up to 600V but with limited current. Can be paralleled quite easily for higher current capability.

- Internal (dynamic) resistance between drain and source during on state, $R_{DS(ON)}$, limits the power handling capability of MOSFET. High losses especially for high voltage device due to $R_{DS(ON)}$.

- Dominant in high frequency application (>100kHz). Biggest application is in switched-mode power supplies.
Insulated Gate Bipolar Transistor (IGBT)

IGBT: symbol

v-i characteristics

- Combination of BJT and MOSFET characteristics. Compromises include:
  
  - Gate behaviour similar to MOSFET - easy to turn on and off.
  
  - Low losses like BJT due to low on-state Collector-Emitter voltage (2-3V).
IGBT

- Ratings: Voltage: $V_{CE} < 3.3kV$, Current: $I_C < 1.2kA$ currently available. Work in under progress for $4.5kV/1.2kA$ device. Constant improvement in voltage and current ratings.

- Good switching capability (up to 100KHz) for newer devices. Typical application, IGBT is used at 20-50KHz.

- For very high power devices and applications, frequency is limited to several KHz.

- Very popular in new products; practically replacing BJT in most new applications.

- “Snubberless” operation is possible. Most new IGBTs do not require snubbers.
Gate turn-off thyristor (GTO)

- Behave like normal thyristor, but can be turned off using gate signal

- However turning off is difficult. Need very large reverse gate current (normally 1/5 of anode current)
GTO

- Ratings: Voltage: $V_{ak} < 5kV$; Current: $I_a < 5kA$. Highest power ratings switch. Frequency $< 5KHz$.

- Gate drive design is very difficult. Need very large reverse gate current to turn off. Often custom-tailored to specific application.

- Currently getting very stiff competition from high power IGBT. The latter has much simpler and cheaper drivers.

- GTO normally requires snubbers. High power snubbers are expensive.

- In very high power region ($> 5kV$, $> 5kA$), development in gate-controlled thyristor (GCT) may effectively end the future of GTO.
(Base/gate) Driver circuit

- Interface between control (low power electronics) and (high power) switch. Functions:
  - amplifies control signal to a level required to drive power switch
  - provides electrical isolation between power switch and logic level

- Complexity of driver varies markedly among switches. MOSFET/IGBT drivers are simple but GTO drivers are very complicated and expensive.
Example: simple MOSFET gate driver

- Note: MOSFET requires $V_{GS} = +15V$ for turn on and 0V to turn off. LM311 is a simple amp with open collector output Q1.

- When $B_1$ is high, $Q_1$ conducts. $V_{GS}$ is pulled to ground. MOSFET is off.

- When $B_1$ is low, $Q_1$ will be off. $V_{GS}$ is pulled to $V_{GG}$. If $V_{GG}$ is set to +15V, the MOSFET turns on.
Gate drive for thyristors

- Pulse transformer is used for isolation. $R_1$ is to limit the gate current.

- Normally a pulse with length 10us with amplitude of 50mA is sufficient to turn-on the thyristors. It is quite common to fire the thyristors with successive pulses to ensure proper turn-on.

- It is not possible to turn-off a thyristor with the above circuit.
Electrical isolation for drivers

- Isolation is required to prevent damages on the high power switch to propagate back to low power electronics.

- Normally opto-coupler (shown below) or high frequency magnetic materials (as shown in the thyristor case) are used.

![Opto-coupler isolation diagram](image)

- Many standard driver chips have built-in isolation. For example TLP 250 from Toshiba, HP 3150 from Hewlett-Packard uses opto-coupling isolation.
## Switches comparisons (2000)

<table>
<thead>
<tr>
<th></th>
<th>Thy</th>
<th>BJT</th>
<th>FET</th>
<th>GTO</th>
<th>IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Availability</strong></td>
<td>Early 60s</td>
<td>Late 70s</td>
<td>Early 80s</td>
<td>Mid 80s</td>
<td>Late 80s</td>
</tr>
<tr>
<td><strong>Voltage ratings</strong></td>
<td>5kV</td>
<td>1kV</td>
<td>500V</td>
<td>5kV</td>
<td>3.3kV</td>
</tr>
<tr>
<td><strong>Current ratings</strong></td>
<td>4kA</td>
<td>400A</td>
<td>200A</td>
<td>5kA</td>
<td>1.2kA</td>
</tr>
<tr>
<td><strong>Switch Freq.</strong></td>
<td>na</td>
<td>5kHz</td>
<td>1MHz</td>
<td>2kHz</td>
<td>100kHz</td>
</tr>
<tr>
<td><strong>On-state Voltage</strong></td>
<td>2V</td>
<td>1-2V</td>
<td>I* Rds(on)</td>
<td>2-3V</td>
<td>2-3V</td>
</tr>
<tr>
<td><strong>Drive Circuit</strong></td>
<td>Simple</td>
<td>Difficult</td>
<td>Very simple</td>
<td>Very difficult</td>
<td>Very simple</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>Cannot turn off using gate signals</td>
<td>Phasing out in new product</td>
<td>Good performance in high freq.</td>
<td>King in very high power</td>
<td>Best overall performance.</td>
</tr>
</tbody>
</table>
Application examples

- For each of the following application, choose the best power switches and reason out why.

- An inverter for the light-rail train (LRT) locomotive operating from a DC supply of 750 V. The locomotive is rated at 150 kW. The induction motor is to run from standstill up to 200 Hz, with power switches frequencies up to 10KHz.

- A switch-mode power supply (SMPS) for remote telecommunication equipment is to be developed. The input voltage is obtained from a photovoltaic array that produces a maximum output voltage of 100 V and a minimum current of 200 A. The switching frequency should be higher than 100kHz.

- A HVDC transmission system transmitting power of 300 MW from one ac system to another ac system both operating at 50 Hz, 230 kV rms line to line and the DC link voltage operating at 200 kV.
Power switch losses

• It is important to consider losses of power switches:
  – to ensure that the system operates reliably under prescribed ambient conditions
  – so that heat removal mechanism (e.g. heat sink, radiators, coolant) can be specified. Heat sinks and other heat removal systems are costly and bulky.
  – losses in switches affects the system efficiency

• If a power switch is not cooled to its specified junction temperature, the full power capability of the switch cannot be realised. Derating of the power switch ratings may be necessary.

• Main losses occurs in power switches are
  – forward conduction losses,
  – blocking state losses
  – switching losses
Forward conduction losses

- Ideal switch has zero voltage drop across it during turn-on ($V_{on}$). Although the forward current ($I_{on}$) may be large, the losses on the switch is zero.

- But for real switches, e.g. BJT, IGBT, GTO, SCR, GCT have forward conduction voltage (on state) between 1-3V. MOSFET has on state voltage which is characterised by the $R_{DS(ON)}$. 

\[ I_{on} \rightarrow \begin{array}{c} +V_{on}^- \\ \end{array} \]

Ideal switch

\[ I_{on} \rightarrow +V_{on}^- \]

Real switch
Forward conduction and blocking state losses

- Losses is measured by product of volt-drop across the device $V_{on}$ with the current, $I_{on}$, averaged over the period.

- Forward conduction losses is the major source of loss at low frequency and DC operation.

- During turn-off, the switch blocks large voltage. Ideally no current should flow through the switch. But for real switch a small amount of leakage current may flow. This creates turn-off or blocking state losses

- The leakage current during turn-off is normally very small, Hence the turn-off losses are usually neglected.
Switching losses

- During turn-on and turn off, ideal switch requires zero transition time. Voltage and current are switched instantaneously.

- In real switch, due to the non-idealities of power switches, the switching profile is as shown in above.

- The switching losses occurs as a result of both the voltage and current changing simultaneously during the switching period.
Switching losses

- The product of device voltage and current gives instantaneous power dissipated in the device.

- The heat energy that developed over the switching period is the integration (summation) of instantaneous power over time as shown by the shaded area under the power curve.

- The average power loss is the sum of the turn-on and turn off energies multiplied by the switching frequency.

- When frequency increase, switching losses increases. This limits the usable range of power switches unless proper heat removal mechanism is employed.
Safe Operating Area (SOA)

- Convenient method to summarise maximum values of current and voltage to which the power switch should be subjected;

- Different devices have different SOA. Example of SOA for a typical BJT is shown below.
Snubbers

- PCB construction, wire loops creates stray inductance, $L_s$.
- Using KVL,

$$v_{in} = v_s + v_{ce} = L_s \frac{di}{dt} + v_{ce}$$

$$v_{ce} = v_{in} - L_s \frac{di}{dt}$$

since $di/dt$ is negative (turning off)

$$v_{ce} = v_{in} + L_s \frac{di}{dt}$$

Simple switch at turn off
Snubbers

• From previous equation, the voltage across the switch is bigger than the supply (for a short moment).

• The spike may exceed the switch rated blocking voltage and causes damage due to overvoltage.

• To prevent such occurrence, a snubber is put across the switch. An example of a snubber is an RCD circuit shown below.

• Snubber circuit “smoothened” the transition and make the switch voltage rise more “slowly”. In effect it dampens the high voltage spike to a safe value.

• Switches and diodes requires snubbers. However, new generation of IGBT, MOSFET and GCT do not require it.
RCD Snubbers

- In general, snubbers are used for:
  - turn-on: to minimise large overcurrents through the device at turn-on
  - turn-off: to minimise large overvoltages across the device during turn-off.
  - Stress reduction: to shape the device switching waveform such that the voltage and current associated with the device are not high simultaneously.
## Ideal vs. Practical power switch

<table>
<thead>
<tr>
<th>Ideal switch</th>
<th>Practical switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block arbitrarily large forward and reverse voltage with zero current flow when off</td>
<td>Finite blocking voltage with small current flow during turn-off</td>
</tr>
<tr>
<td>Conduct arbitrarily large currents with zero voltage drop when on</td>
<td>Finite current flow and appreciable voltage drop during turn-on (e.g. 2-3V for IGBT)</td>
</tr>
<tr>
<td>Switch from on to off or vice versa instantaneously when triggered</td>
<td>Requires finite time to reach maximum voltage and current. Requires time to turn on and off.</td>
</tr>
<tr>
<td>Very small power required from control source to trigger the switch</td>
<td>In general voltage driven devices (IGBT, MOSFET) requires small power for triggering. GTO requires substantial amount of current to turn off.</td>
</tr>
</tbody>
</table>
Related websites for further readings/info/data sheet.

• Power switches
  – power diodes (irf.com) (semikron.com)
  – thyristors (irf.com) (semikron.com)
  – IGBT (siemens.com) (irf.com) (toshiba.com),
  – MOSFETS (irf.com)
  – GTO (abb.com)
  – GCT (abb.com)

• Drivers
  – IGBT (toshiba.com), (hp.com) (semikron.com)

• Complete power electronics solutions
  – (abb.com)