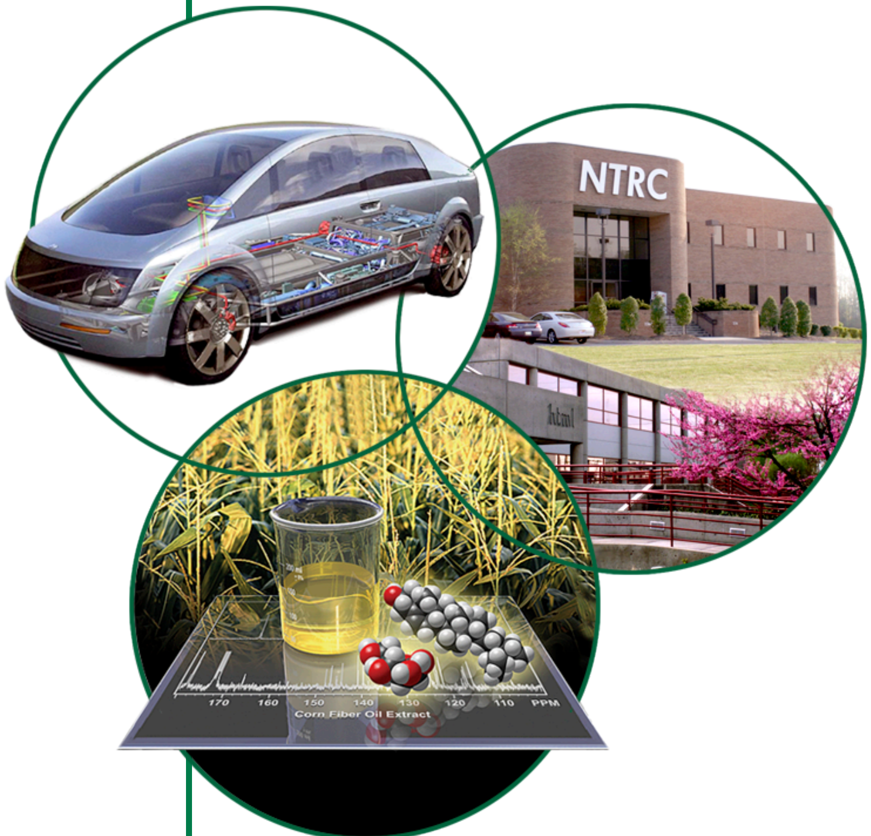
Introduction to Power Electronics - A Tutorial

Burak Ozpineci

Power Electronics and Electrical Power Systems Research Center



U.S. DEPARTMENT OF ENERGY

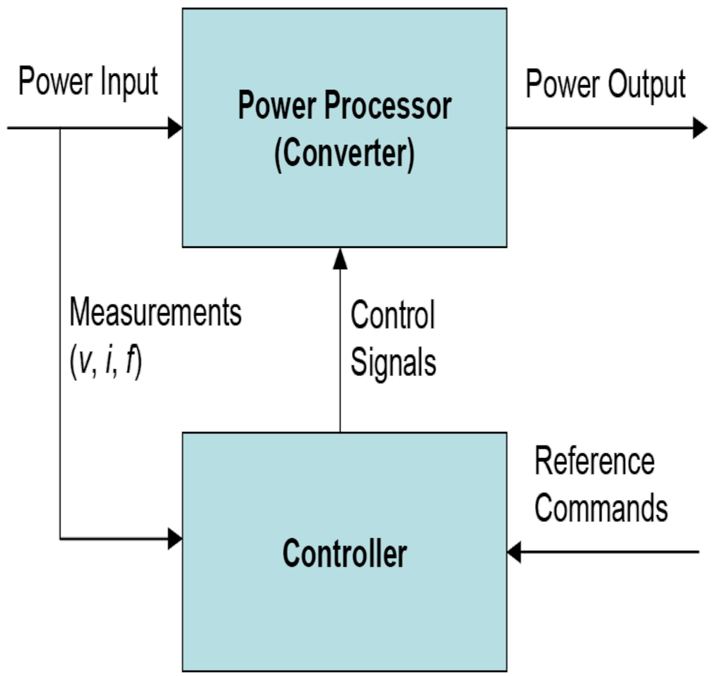
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

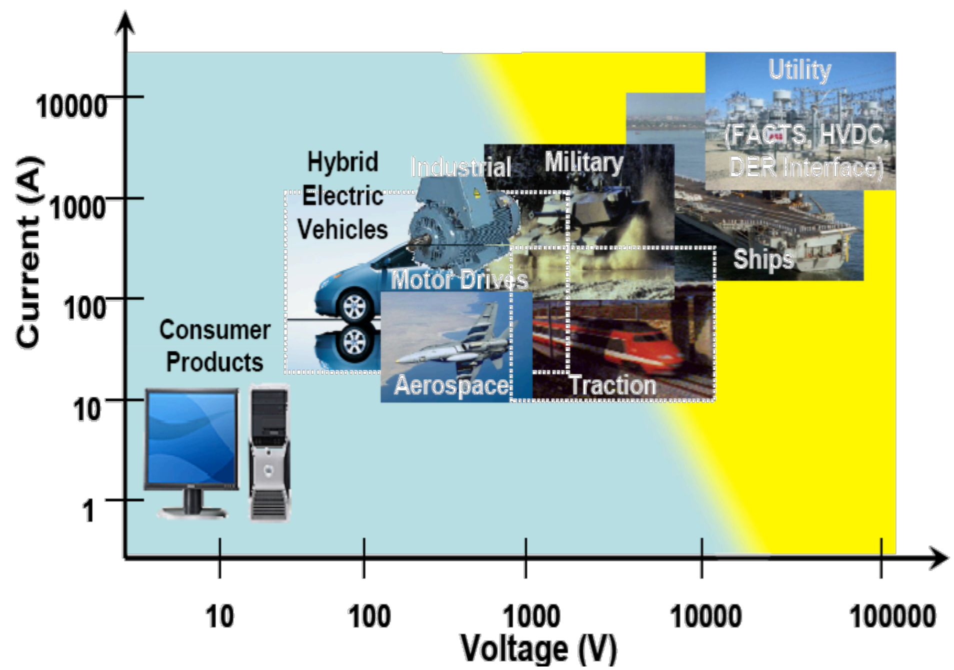
Agenda

1. The definition of power electronics
2. Power semiconductors
3. Power semiconductor losses
4. Types of power converters
5. Power conversion
6. Thermal management

What is Power Electronics?

Power Electronics is used to change the characteristics (voltage and current magnitude and/or frequency) of electrical power to suit a particular application. It is an interdisciplinary technology.

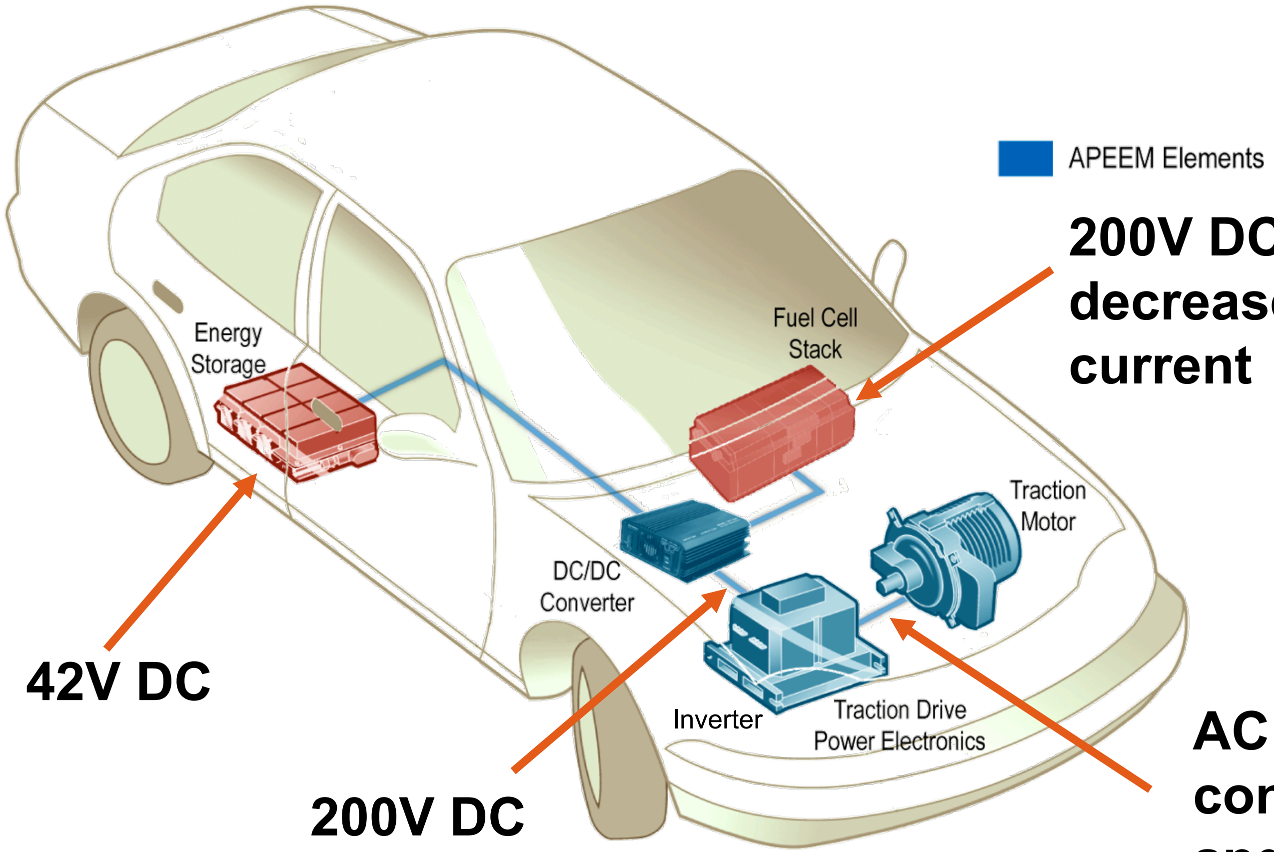




Applications of Power Electronics

- Transportation
  - Electric/ Hybrid Electric Vehicles
  - Electric Locomotives
  - Electric Trucks, Buses, Construction Vehicles, Golf Carts
- Utilities
  - Line transformers
  - Generating systems
  - Grid interface for alternative energy resources (solar, wind, fuel cells, etc.) and energy storage
  - FACTS
  - HVDC
  - Solid state transformer
  - Solid state fault current limiter
  - Solid state circuit breaker
- Industrial/ Commercial
  - Motor drive systems
  - Electric machinery and tools
  - Pumps/ compressors
  - Process control
  - Factory automation
- Consumer Products
  - Air conditioners/ Heat pumps
  - Appliances
  - Computers
  - Lighting
  - Telecommunications
  - Uninterruptible power supplies
  - Battery chargers
- Medical equipment

Fuel Cell Powertrain Hybrid Design



200V DC – inherently decreases with higher current

42V DC

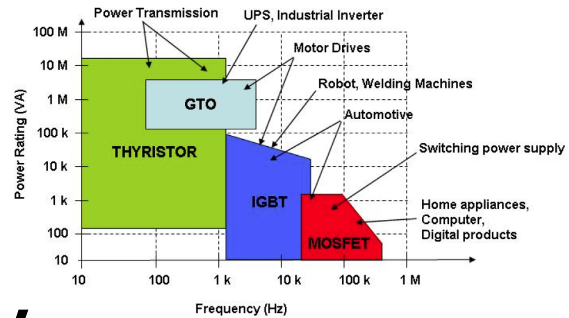
200V DC

AC voltage with controllable voltage and frequency: 0-500V and 0-200Hz

History of Power Devices

- Power diodes (or rectifiers)
- Bipolar transistor – 1948
  - Power BJT (bipolar junction transistor) - 1960
- Thyristor or SCR (Silicon controlled rectifier) - 1957
- Power MOSFETs (Metal oxide semiconductor field effect transistor) - 1970
  - IR 400V 25A power MOSFET 1978
- IGBT (insulated gate bipolar transistor) – 1990 – a hybrid between a MOSFET and a BJT

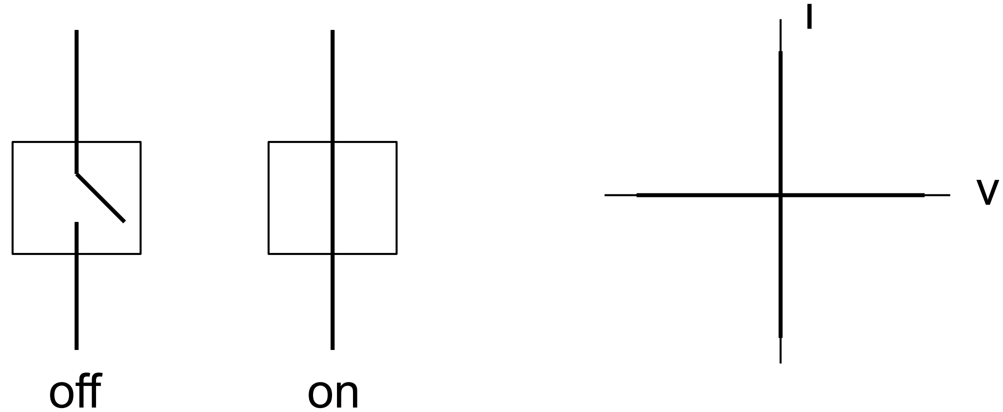
List of typical power devices



- Two terminal devices
  - PiN diodes (for voltages >300V)
  - Schottky diodes (for voltages <300V, no reverse recovery loss)
- Three terminal devices – switches
  - BJT (not used much in power converters, high voltage blocking capability)
  - MOSFET (commonly used for voltage <300V, very fast devices)
  - IGBT (for voltages >300V, a hybrid of BJTs and MOSFETs)
  - Thyristors – GTO, IGCT, ETO, MCT, etc. (high voltage applications)

Ideal Characteristics of a Power Device

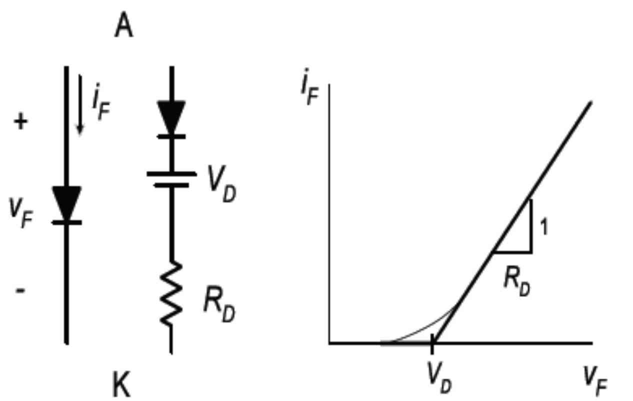
1. Block arbitrarily large forward and reverse voltages with zero current flow when off.
2. Conduct arbitrarily large currents with zero voltage drop when on. – *no conduction losses*
3. Switch from off to on or vice versa instantaneously. – no switching losses
4. Negligible power (small voltage or current) required to trigger switch. – for controllable switches
5. Free



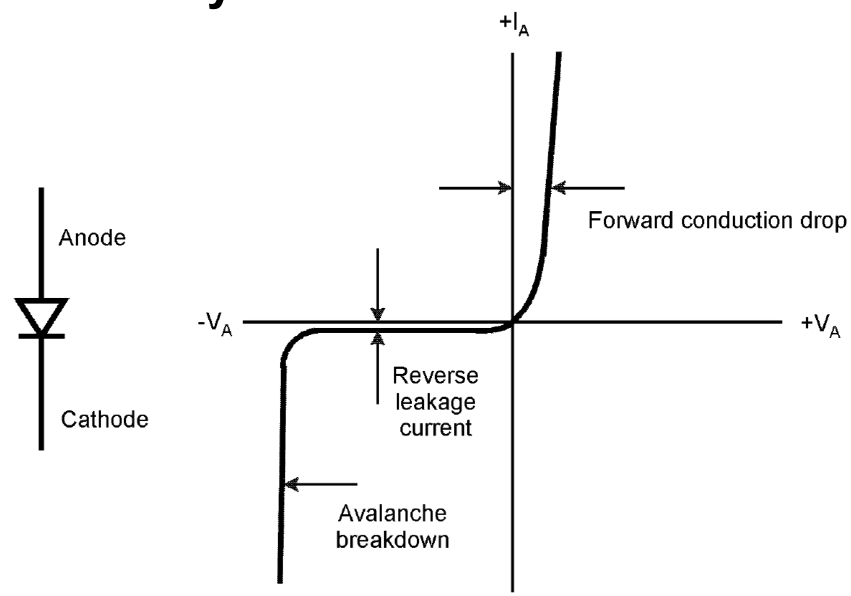
Power Diode/Rectifier

- Diodes block voltage in reverse direction and allow current in forward direction.
- They start conduction once the voltage in the forward direction goes beyond a certain value.

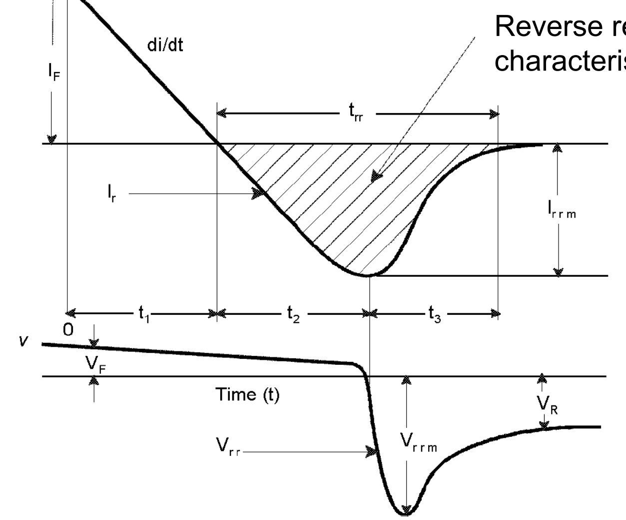
Piece-wise linear model



Diode symbol and I-V characteristics



Diode turn-off characteristics



Insulated Gate Bipolar Transistor

- IGBTs are preferred devices for voltages above 300V and below 5kV.
- They are turned on and off by applying low voltage voltage pulses to their gate.

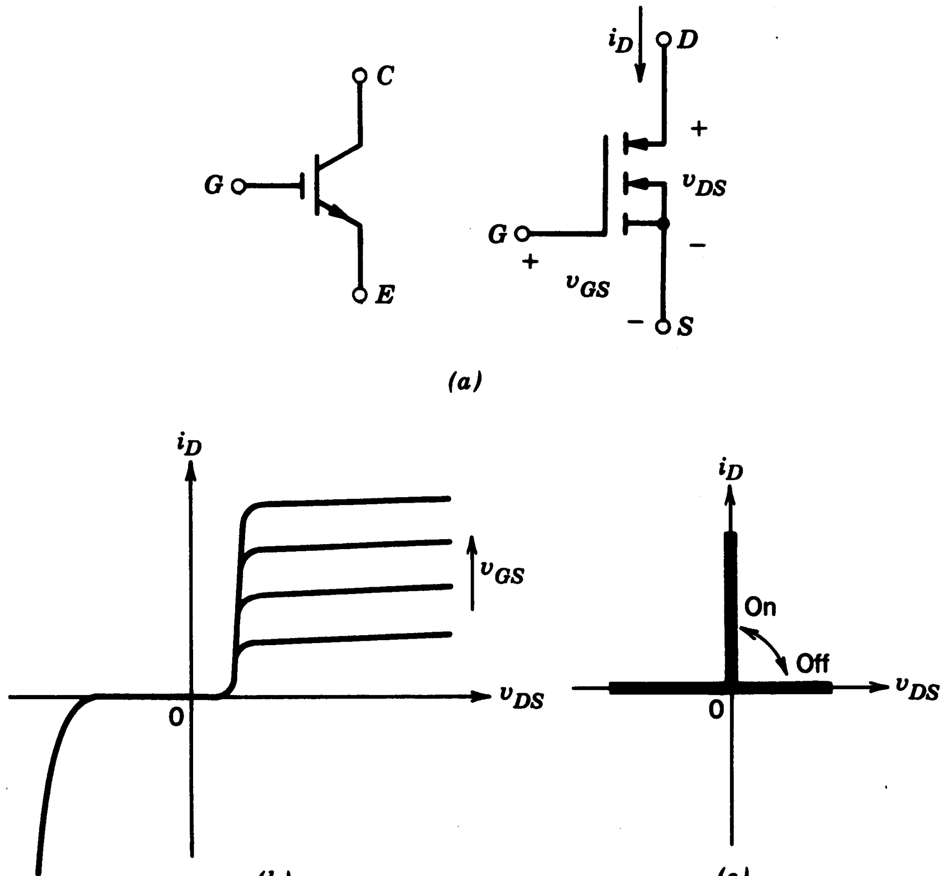


Figure 2-12 An IGBT: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Desirable Characteristics of a Power Device

1. Small leakage current in off state.
2. Small on-state voltage drop to minimize conductive losses.
3. Short turn-on and turn-off times (high switching frequency).
4. Large forward and reserve voltage blocking capability minimizes need to series several devices.
5. High on-state current rating minimizes need to parallel devices.

Desirable Characteristics of a Power Device (cont')

6. Positive temperature coefficient for on-state resistance. This helps ensure paralleled devices share current equally.
7. Small control power (low voltage or current) to gate (switch) devices.
8. Capability to withstand rated current or voltage when switching. eliminates need for snubbers (external protection).
9. Capability to withstand large *dv/dt* and *di/dt*, again so that external protection circuits are not needed.

Switching Characteristics

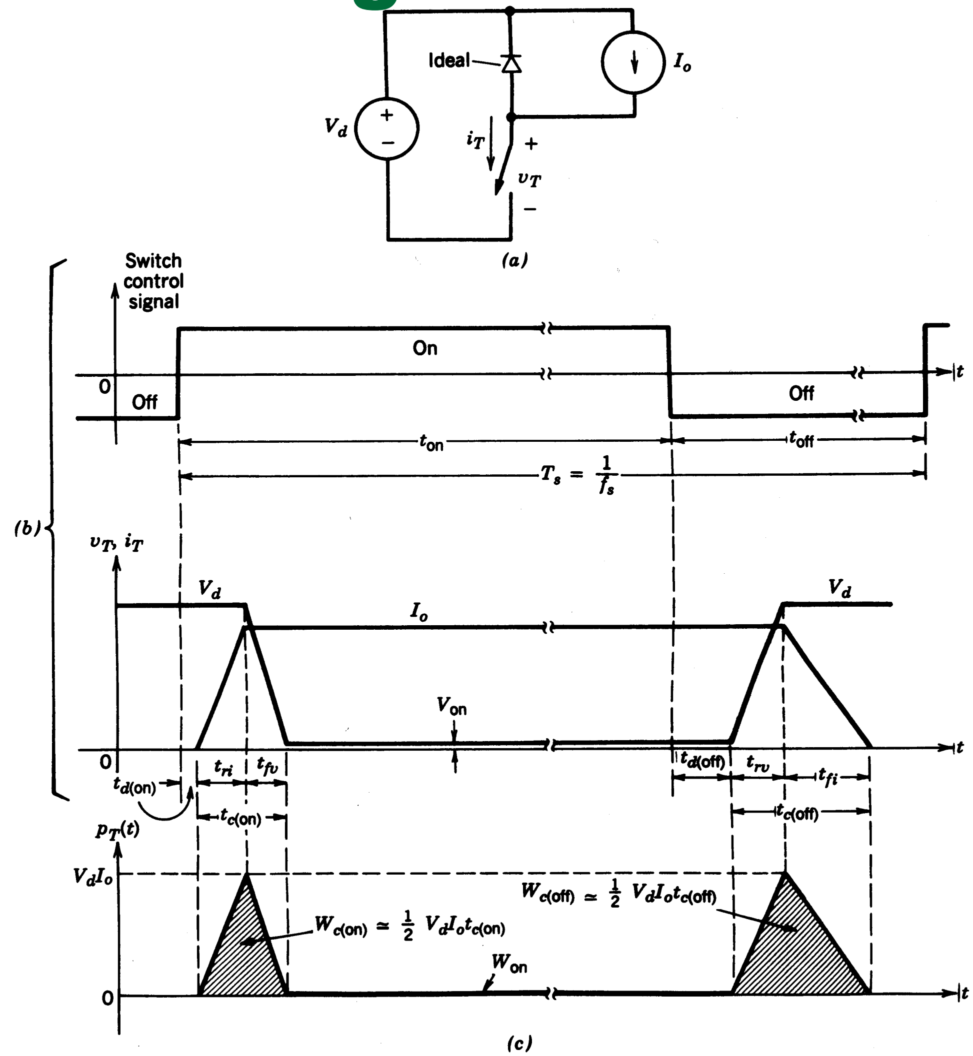


Figure 2-6 Generic-switch switching characteristics (linearized): (*a*) simplified clamped-inductive-switching circuit, (*b*) switch waveforms, (*c*) instantaneous switch power loss.

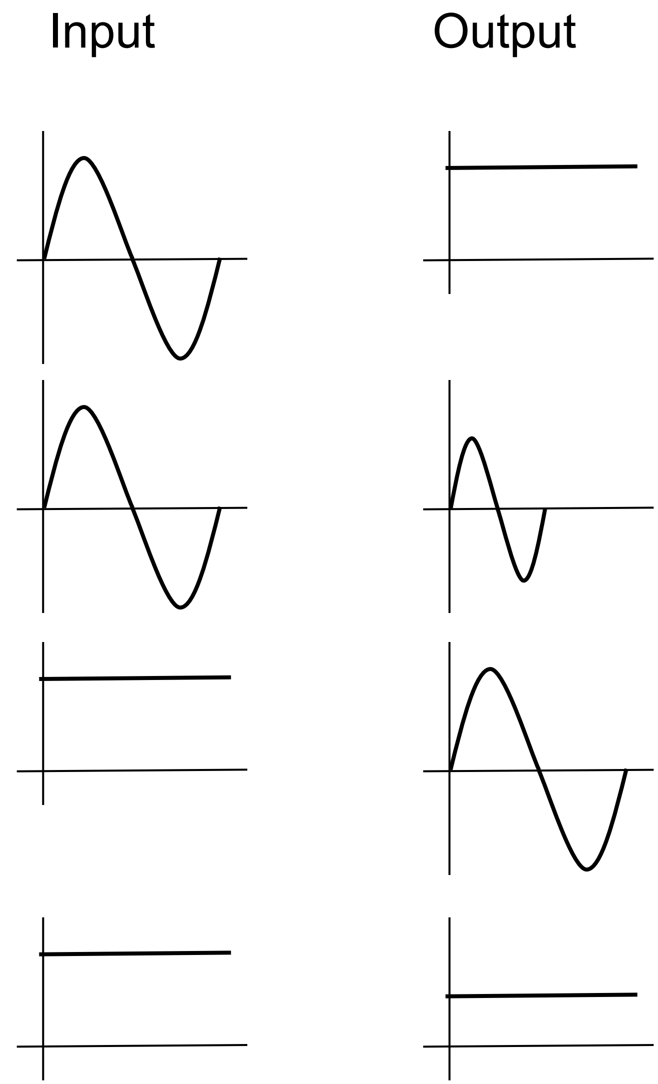
The switching losses increase with

- Increasing switching frequency
- The turn on and off times

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Types of Power Conversion

- **AC-DC Converter (Rectifier)**
  - **Converts input AC to variable magnitude DC, e.g. battery chargers, computer power supplies**
- **AC-AC Converter (Cycloconverter or Frequency Changer)**
  - **Converts input AC to variable magnitude variable frequency AC, e.g. ship propulsion systems**
- **DC-AC Converter (Inverter)**
  - **Converts input DC to variable magnitude variable frequency AC, e.g. electric/hybrid electric traction drives**
- **DC-DC Converter (DC Chopper - Buck/Boost/ Buck-Boost Converter)**
  - **Converts input DC to variable magnitude DC, e.g., voltage regulators**



Applications of Power Converters

DC-DC converters - Switched Mode Power Supplies (SMPS) - Makes up about 75% of power electronics industry.

- Power Supplies for Electronic Equipment
- Robotics
- Automotive/Transportation
- Switching Power Amplifiers
- Photovoltaic Systems

DC-AC - Inverter

- AC Machine Drive (permanent magnet, switched reluctance, or induction machine)
- Uninterruptible Power Supply (UPS)
- Machine Tools
- Induction Heating — Steel Mills
- Locomotive Traction
- Static Var Generation (Power Factor Correction)
- Photovoltaic or Fuel Cell Interface with Utility

AC-DC - rectifier

- DC Machine Drive
- Input Stage to DC/DC or DC/AC Converter
- Energy Storage Systems
- Battery Chargers
- Aerospace Power Systems
- Subways, Trolleys
- High Voltage DC (HVDC) Transmission

AC-AC Converters - Voltage Controller 1Φ to 3Φ Converters

- Lighting /Heating Controls
- Large Machine Drives

Rectification – Single phase, half wave

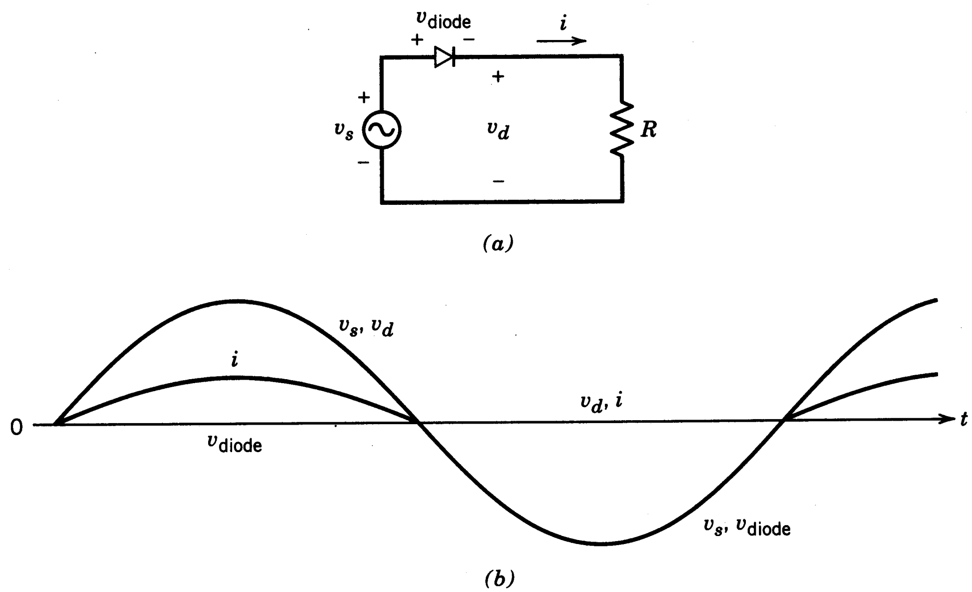
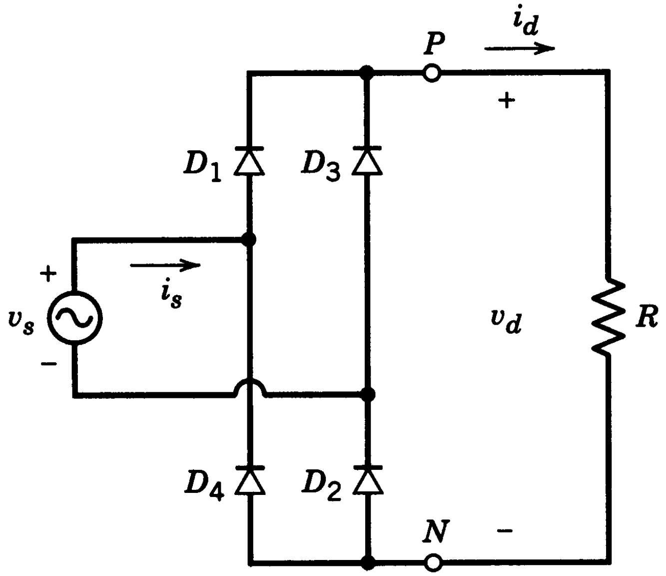
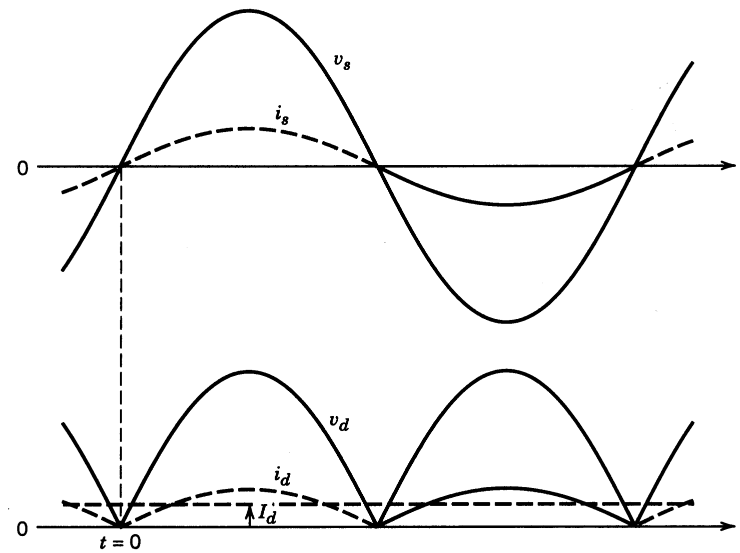


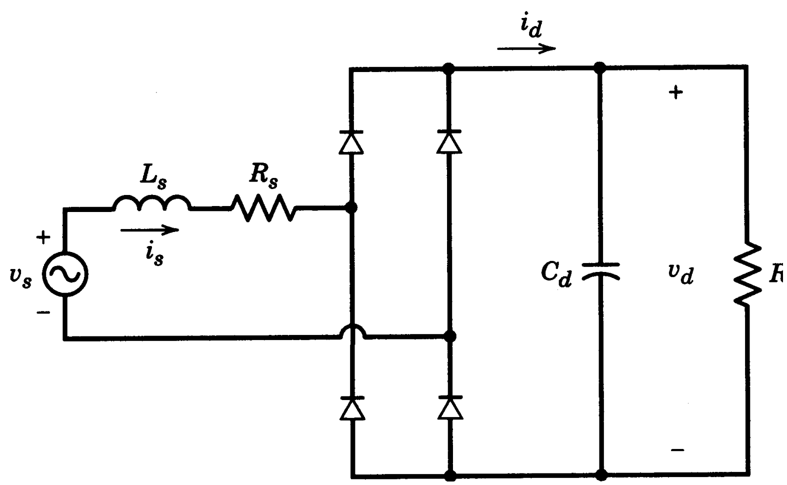
Figure 5-2 Basic rectifier with a load resistance.

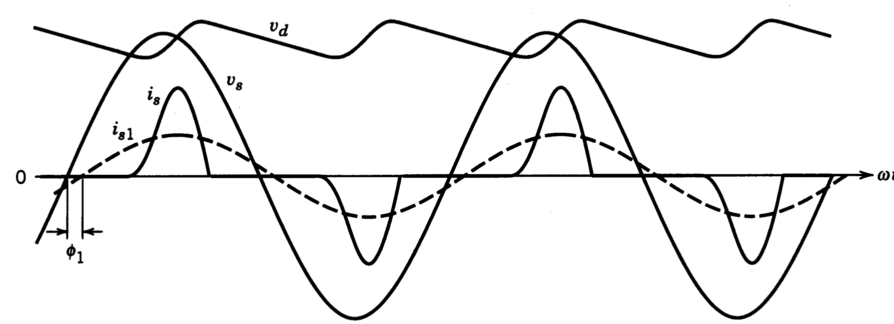
Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Rectification – Single phase – full wave









Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Rectification- three phase, full bridge

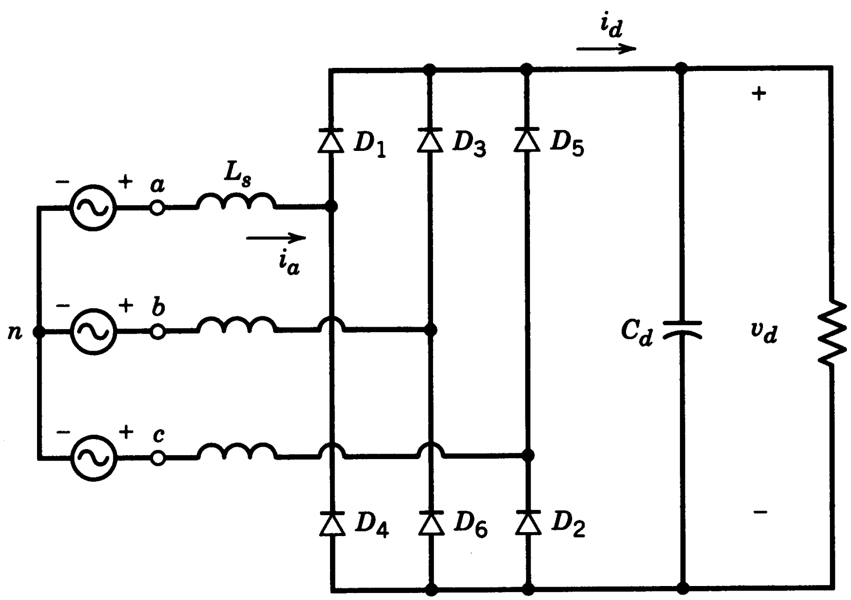


Figure 5-30 Three-phase, full-bridge rectifier.

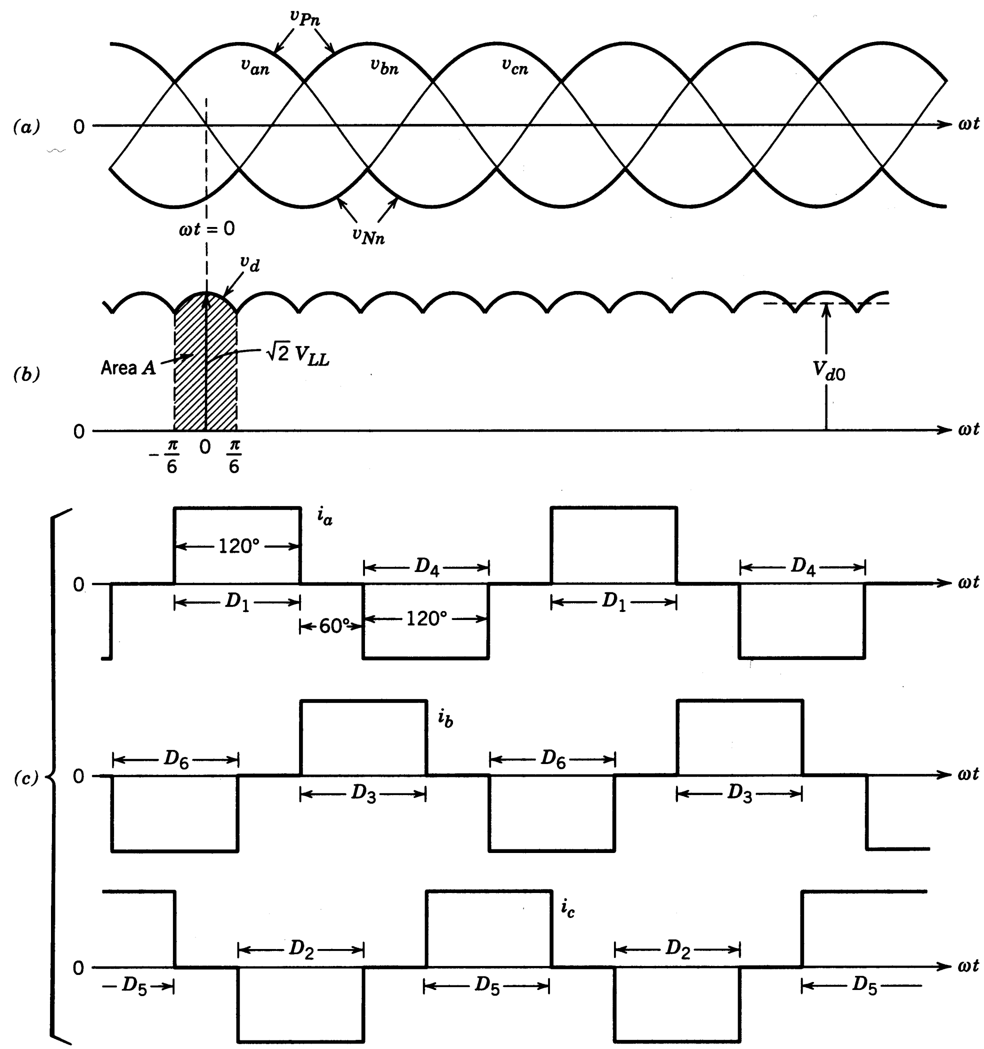


Figure 5-32 Waveforms in the circuit of Fig. 5-31.

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Three-phase rectifier with large filter capacitor

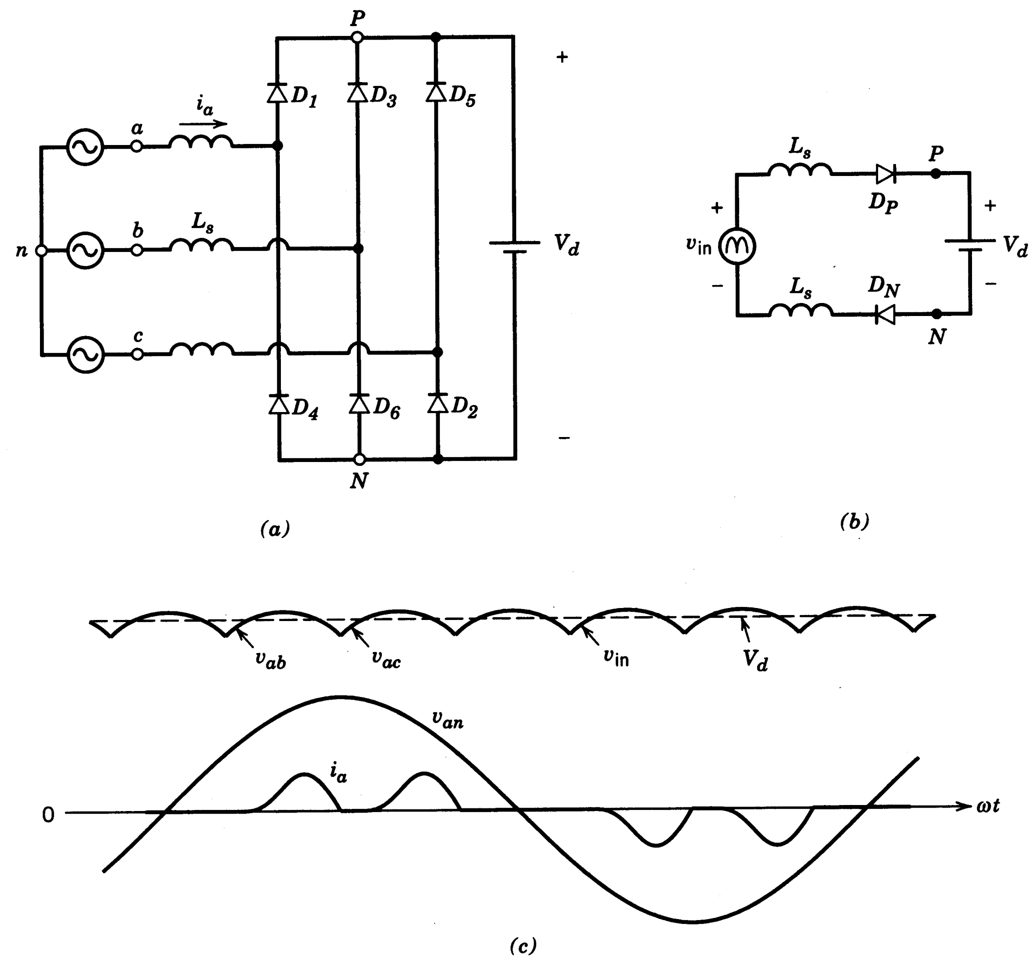


Figure 5-36 (*a*) Three-phase rectifier with a finite L_s and a constant dc voltage. (*b*) Equivalent circuit. (*c*) Waveforms.

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

DC-DC Conversion

Step down converter

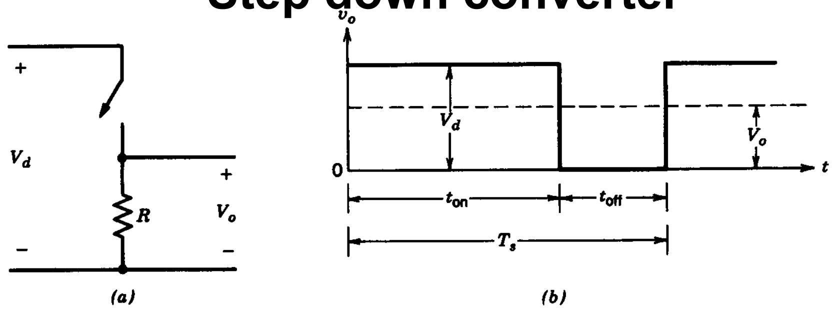
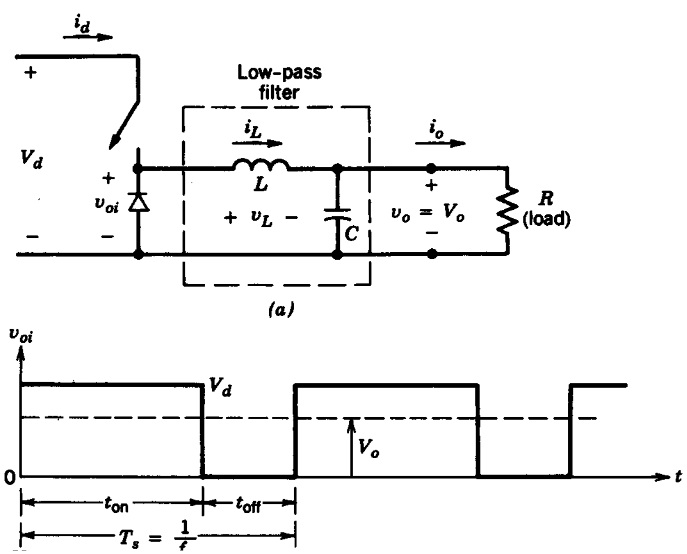
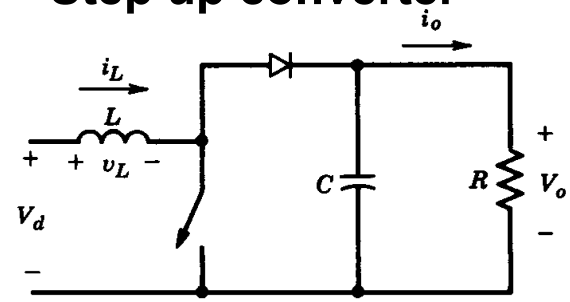


Figure 7-2 Switch-mode dc–dc conversion.



Step up converter



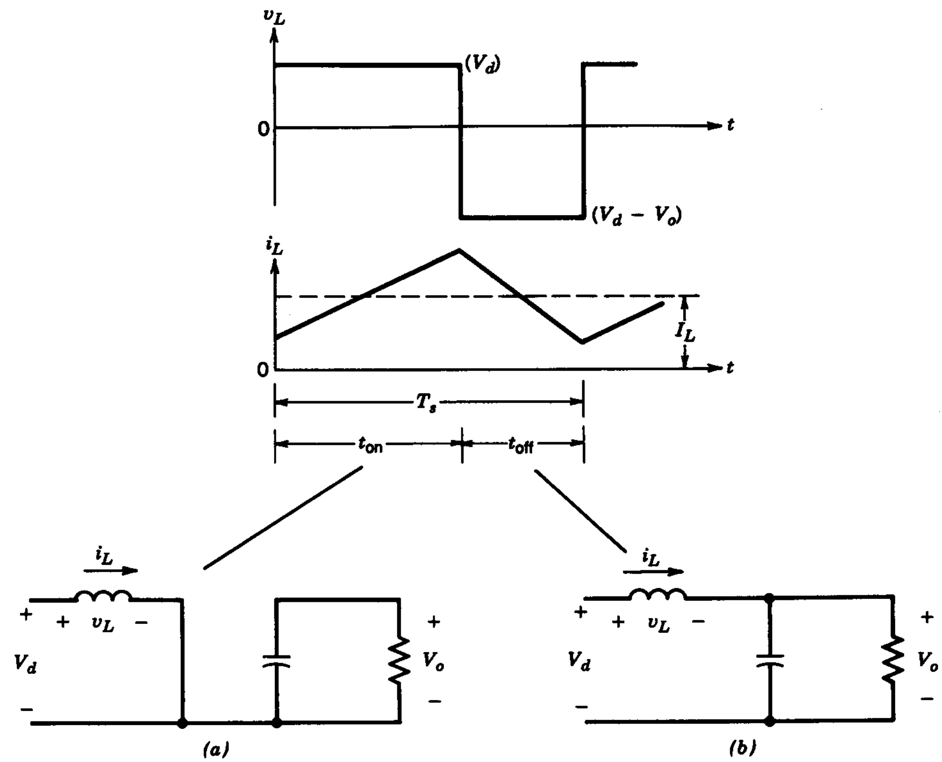
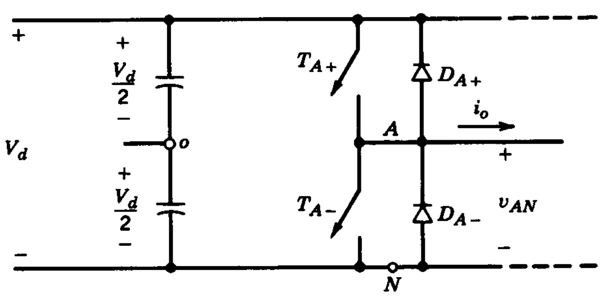


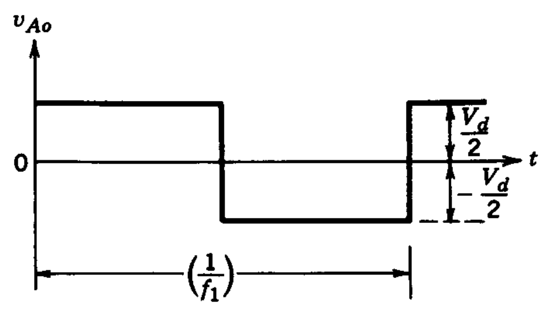
Figure 7-12 Continuous-conduction mode: (*a*) switch on; (*b*) switch off.

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

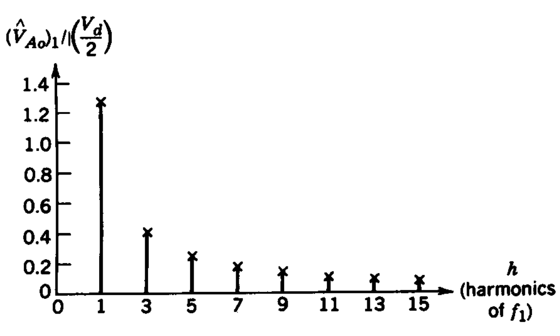
Inverters



Square wave operation

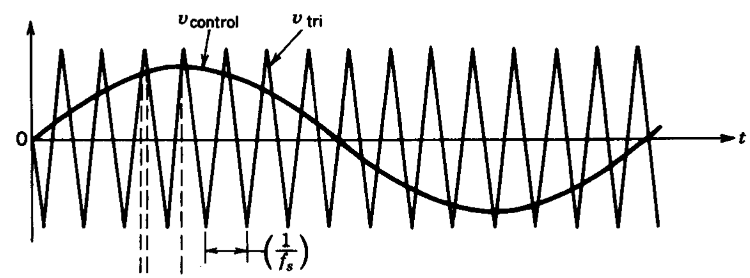


(a)

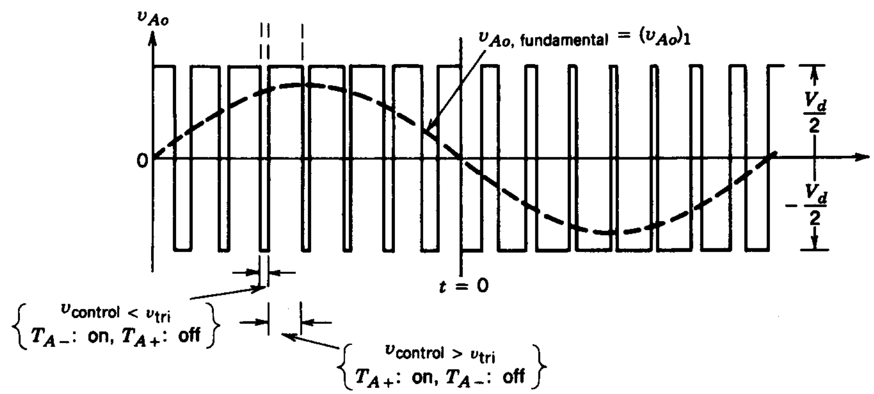


(b)

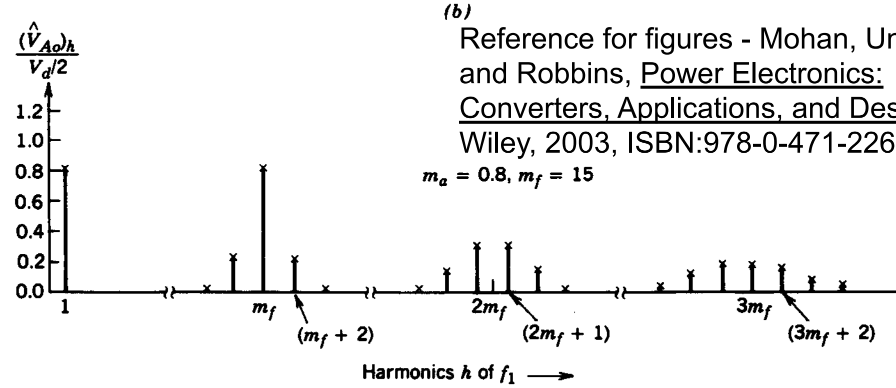
PWM operation



(a)



(b)



(c)

Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Three-phase inverters

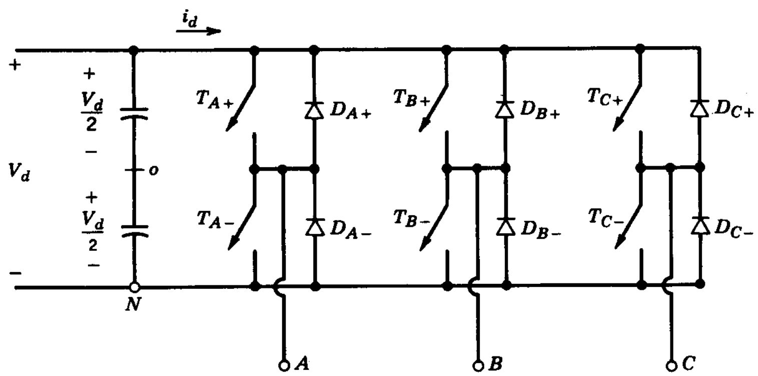
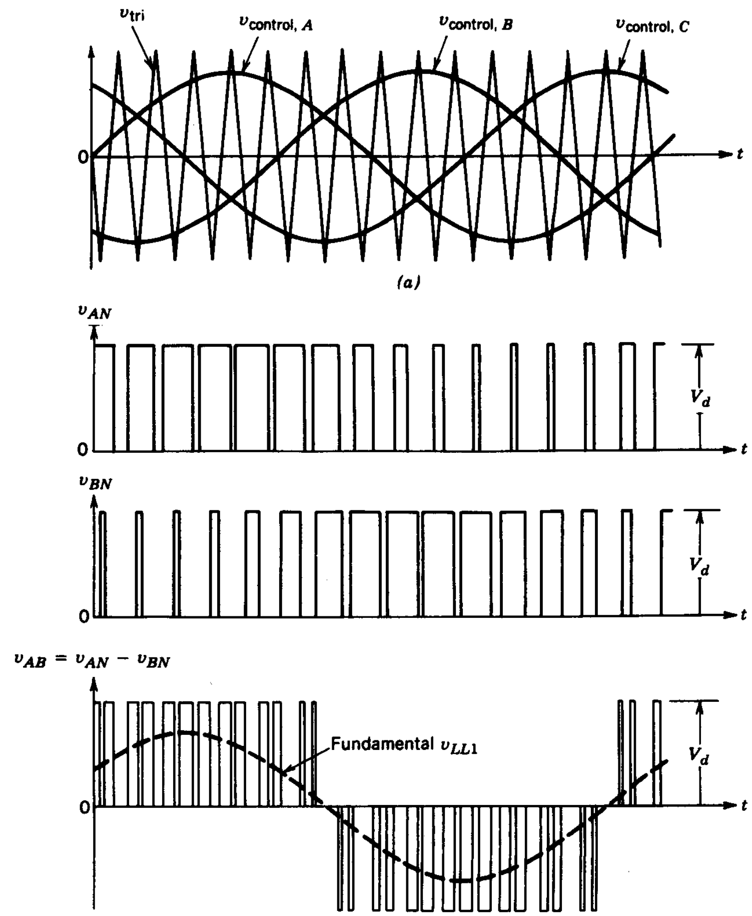


Figure 8-21 Three-phase inverter.



Reference for figures - Mohan, Undeland, and Robbins, Power Electronics: Converters, Applications, and Design, Wiley, 2003, ISBN:978-0-471-22693-2

Component Temperature Control

1. For high reliability, the worst-case junction temperature in semiconductor devices is typically limited to less than 125C.
2. Some Si semiconductor devices can operate at up to 200C, but their lifetime will be low and they likely will have poor performance characteristics. Also, manufacturers will not guarantee parameters above the maximum temperature of 125-150C.
3. Failure rate for semiconductor devices doubles for each 10-15C temperature rise above 50C.

Component Temperature Control (cont')

4. Best for heat sink fins to be vertical and have ample room for natural convection without a fan
5. Heat sink cooling methods

   1) Natural convection

   2) Forced air-fan(ac fan is more reliable than a dc fan)

   3) Liquid cooling—requires a radiator and a pump

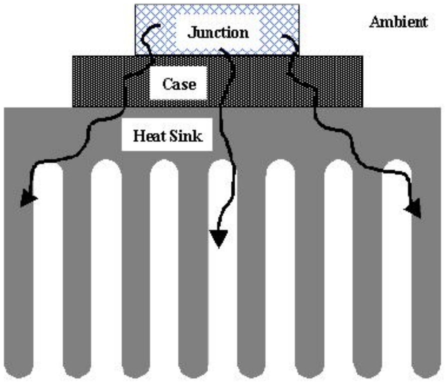


Fig. 6.2. A simplified thermal management system with finned heat sink.

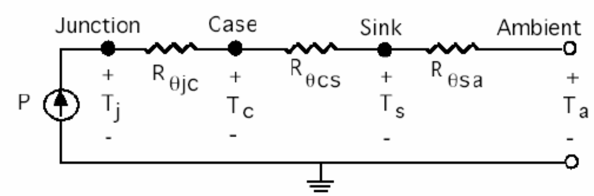
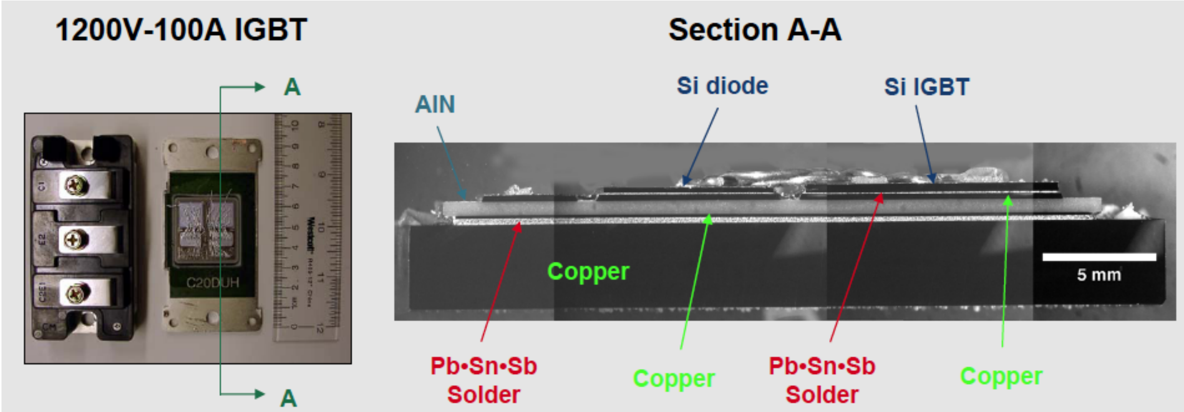
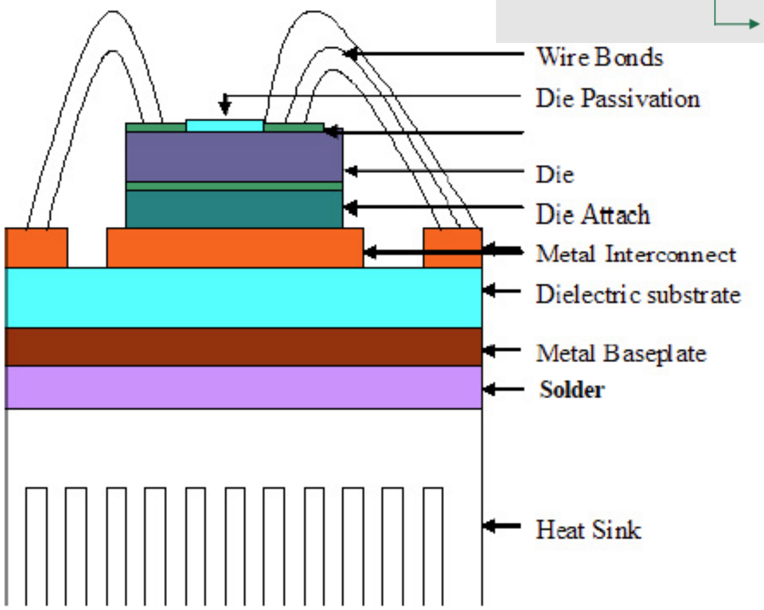


Fig. 6.3. System-level simulation model of the heat sink system in Fig. 6.2.

Device Packaging and Power module





Courtesy of ORNL's
A. Wereszczak and G. Muralidharan

A typical package consists of multiple materials with distinctly different properties