INTRODUCTION TO POWER ELECTRONICS

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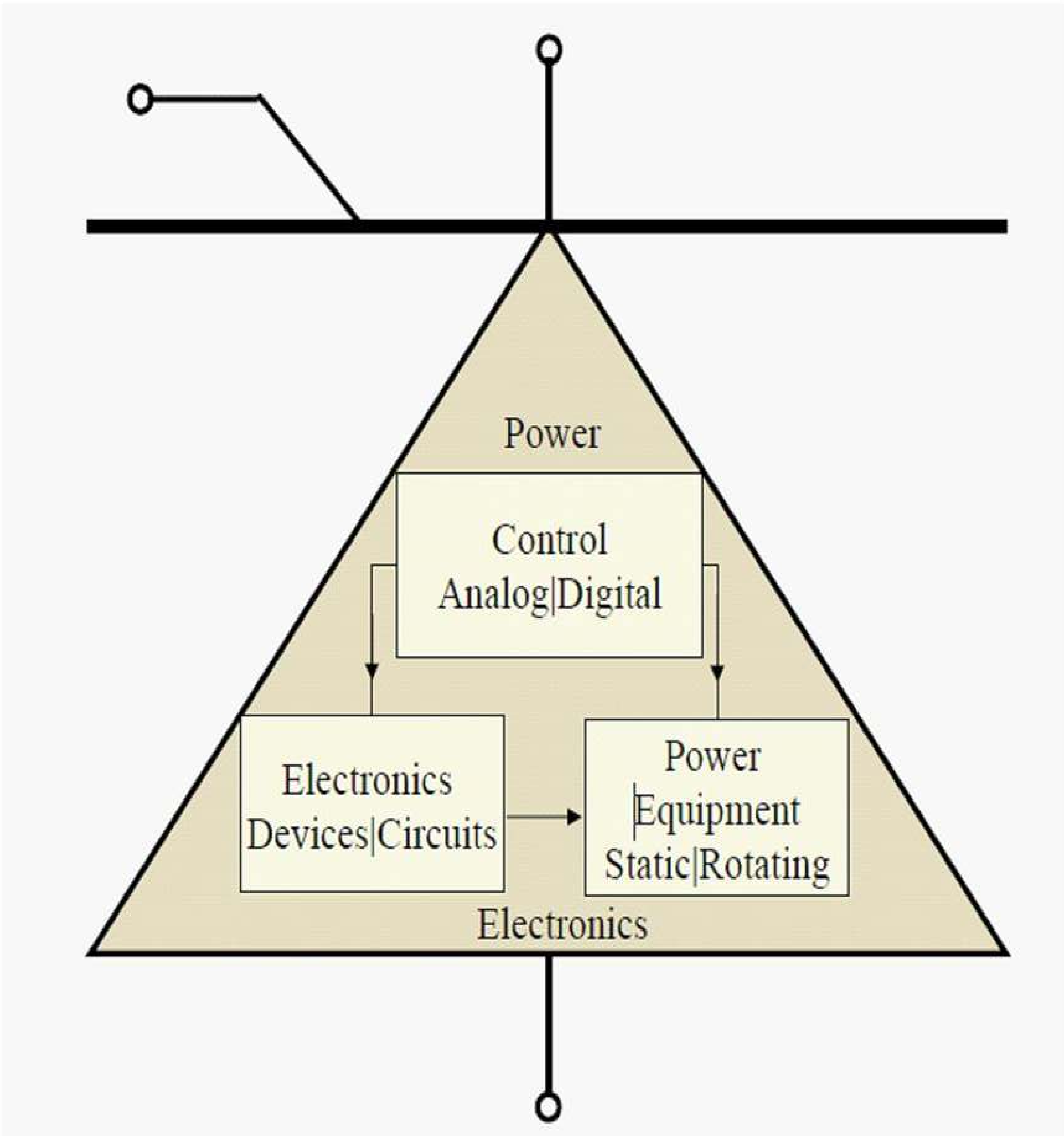
DEFINITION & HISTORY

- Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches.
- Advent of Silicon-Controlled Rectifiers, abbreviated as SCRs, led to the development of a new area of application called the Power Electronics.
- Prior to the introduction of SCRs, mercuryarc rectifiers (1900) were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited.
- Once the SCRs were available (1957), the application area spread to many fields such as drives, power supplies, aviation electronics, high frequency inverters and power electronics originated.

APPLICATIONS OF POWER ELECTRONICS

- Power electronics has applications that span the whole field of electrical power systems, with the power range of these applications extending from a few VA/Watts to several MVA/MW.
- The main task of power electronics is to control and convert electrical power from one form to another form.

Power electronics is a subject of interdisciplinary nature.

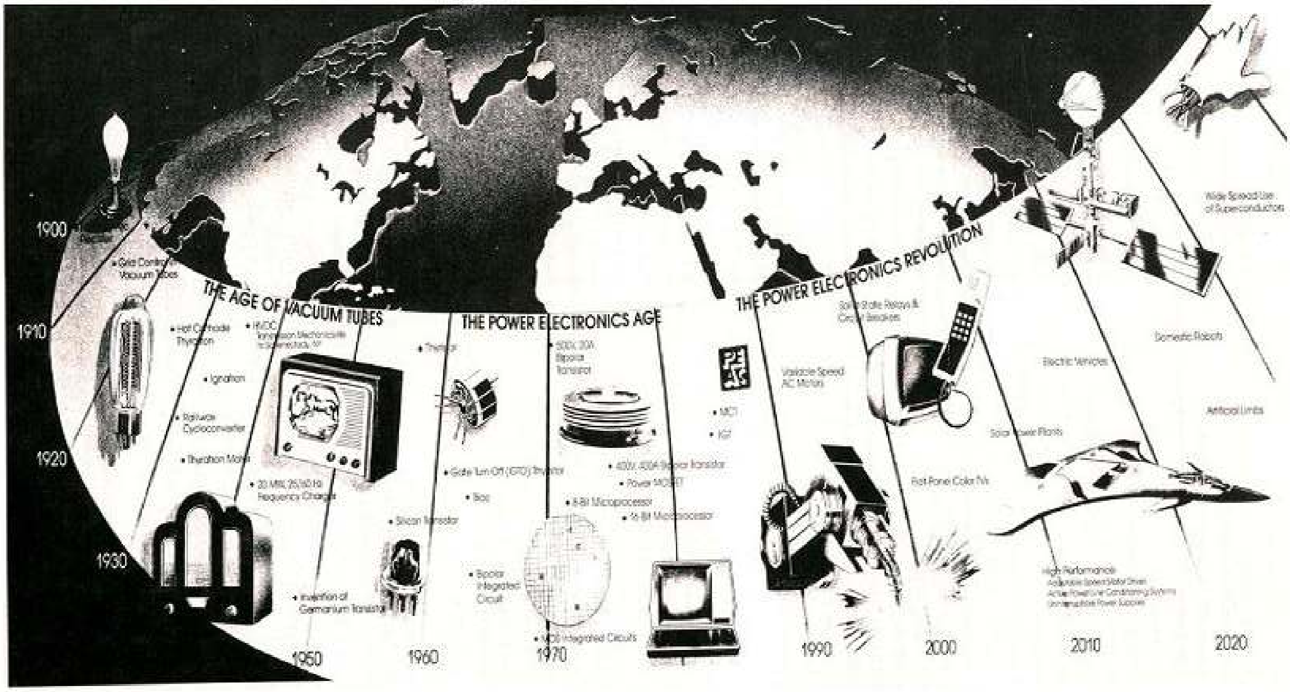


Some Applications of Power Electronics

- ☐ Adverting
- ☐ Air conditioning
- ☐ Aircraft power supplies
- ☐ Alarms
- ☐ Household Appliances
- ☐ Battery charger
- ☐ Chemical processing
- ☐ Computers
- ☐ Cranes, hoists, elevators
- ☐ Dimmers
- ☐ Displays
- ☐ Electric door openers
- ☐ Electric dryers, fans
- ☐ Electric vehicles & traction
- ☐ Electromagnets
- ☐ Gas turbine starting
- ☐ Generator exciters
- ☐ High voltage dc (HVDC)
- ☐ Motor drives
- ☐ Movie projector
- ☐ Oil well drilling
- ☐ Paper mills
- ☐ Photograph, photocopy machines
- ☐ TV, Radio, VCR
- ☐ Solar power supplies, etc…

PO POWER SEMICONDUCTOR DEVICESS

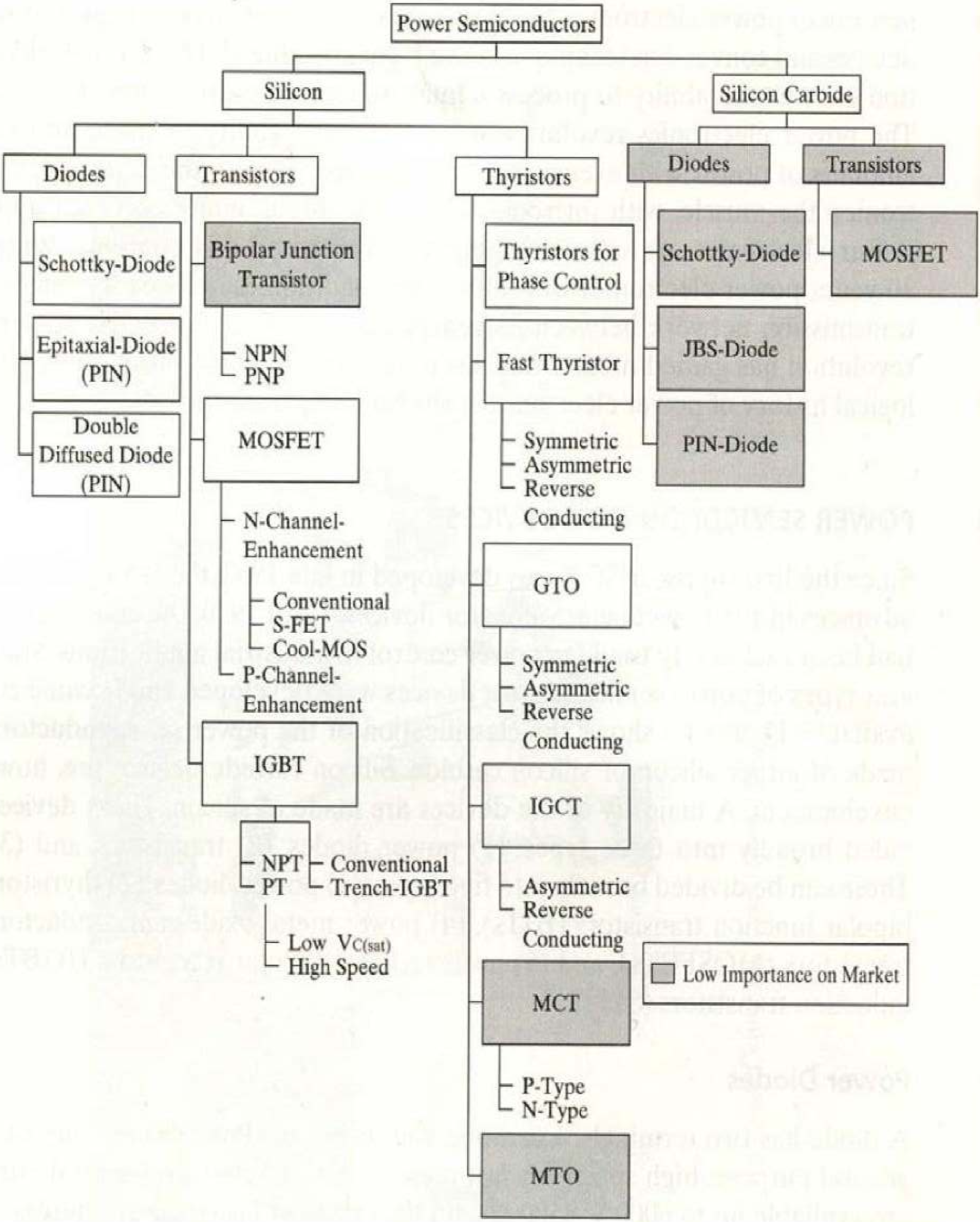
- Since the first thyristor (SCR) was developed in late 1957, there has been tremendous advances in the power semiconductor devices.
- Since 1970 various types of power semiconductor devices were developed and became commercially available.



- Power semiconductor devices are made of either silicon or silicon carbide.
- These devices can be divided broadly into three main types:

✓ Power diodes
✓ Thyristors
✓ Transistors

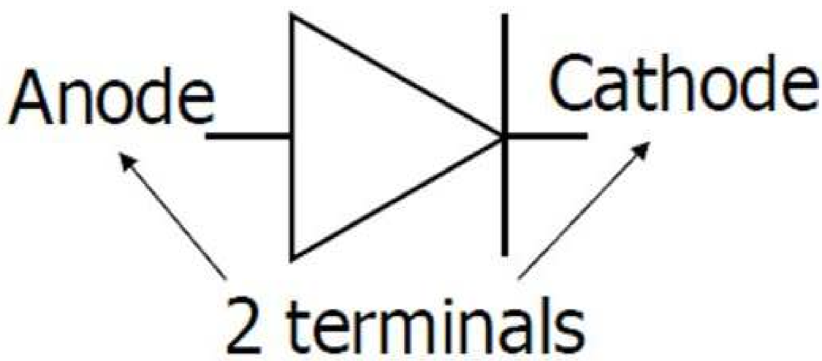
Classification of power semiconductors



Power Diodes

- General purpose
  - Rating up to 6000V, 4500A
- High speed (or fast recovery)
  - ✓Rating up to 6000V, 1100A
  - ✓Reverse recovery time 0.1 to 5μs
  - ✓Essential for high-frequency switching
- Schottky
  - ✓Low on-state voltage
  - ✓Very small recover time (typically nanoseconds).
  - ✓Leakage current increases with voltage rating
  - ✓Rating limited to 100V, 300A

- Conducts when its anode voltage is higher then that of the cathode ($V_A > V_C$)
- Forward voltage drop (when on) is very low (typically 0.5 and 1.2V)
- If $V_C > V_A$ the diode is said to be in blocking mode.



Power Diodes (cont.)

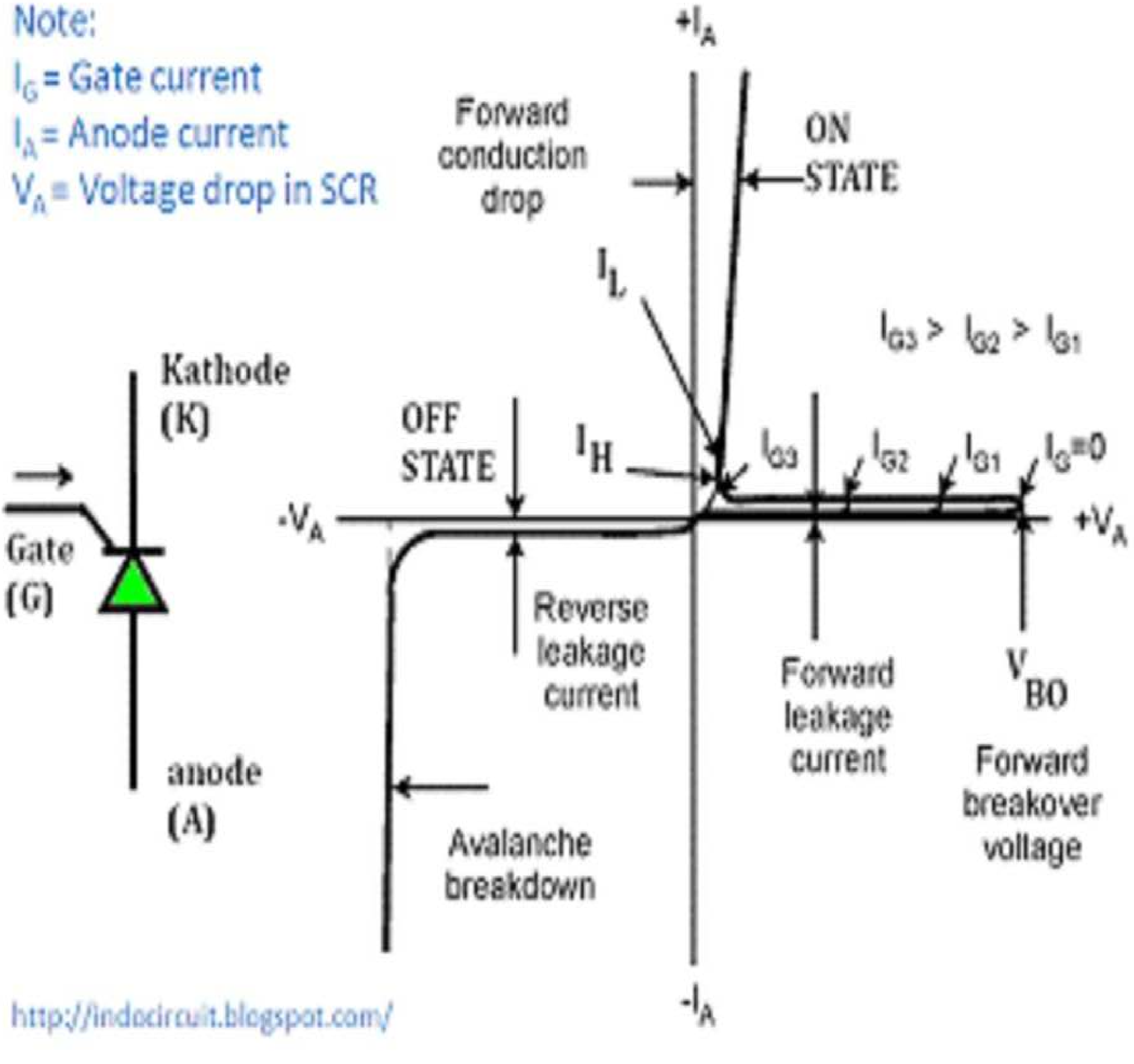
Thyristors

- When a small current is passed through the gate terminal to cathode, the thyristor conducts provided that the anode terminal is at higher potential than that of the cathode:
  - ✓ $i_G > 0$
  - ✓ $V_A > V_C$

- Once a Thyristor is in a conduction mode, the gate circuit has no control and the thyristor continues to conduct.
- In conduction mode, forward voltage is very small (0.5 to 2 V).
- Thyristor can be turned off by making $V_{AC} \leq 0V$
  - ✓ Line-commutated thyristors are turned off due to the sinusoidal nature of their input voltage
  - ✓ Forced-commutated thyristors are turned off by an extra circuit called commutation circuitry.

- Natural or line-commutated thyristors are available with rating up to 6000 V,4500A.
- Turn-off-time became very small (10 to 20 μs in 3000 V, 3600A).

Thyristors (cont.)



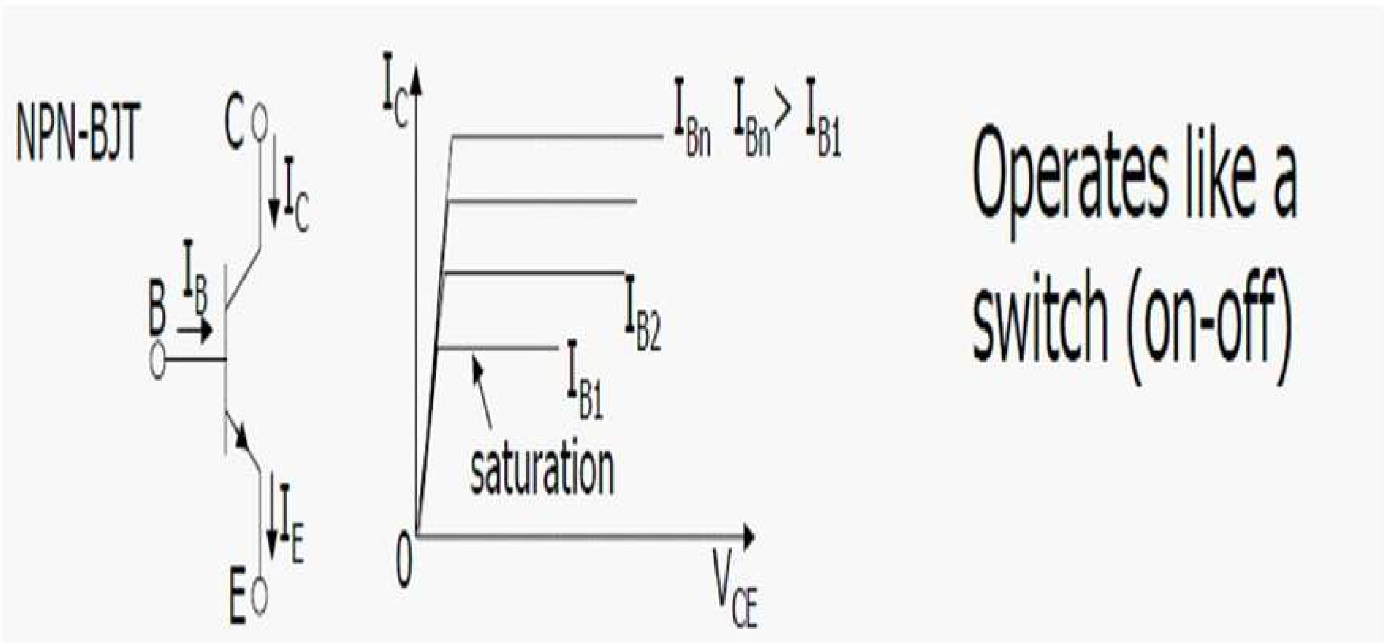
➢ **Can be subdivided into 11 types:**

1. Forced-commutated
2. Line-commutated
3. Gate-Turn-Off (GTO)
4. Reverse Conducting Thyristor (RCT)
5. Static Induction Thyristor (SITH)
6. Gate-Assisted turn off Thyristor (GATT)
7. Light-activated Silicon-Controlled Rectifier (LASCR)
8. MOS Turn-Off (MTO)
9. Emitter Turn-Off (ETO)
10. Integrated Gate- Commutated Thyristor (IGCT)
11. MOS Controlled Thyristors (MCTs)

Power Transistors

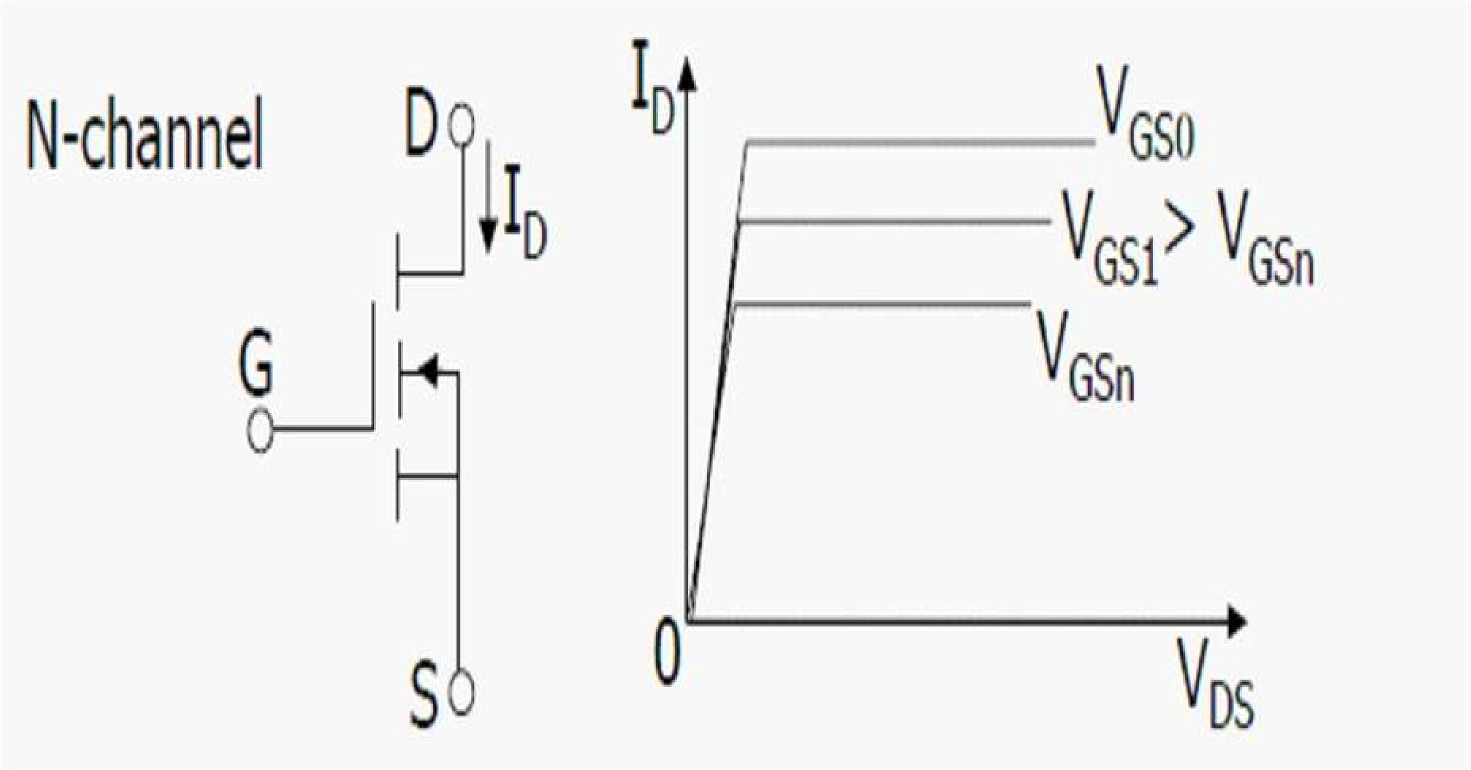
- There are 4 types:
  - ✓Bipolar Junction Transistors (BJTs)
  - ✓Power MOSFETS
  - ✓Insulated-Gate Bipolar Transistors (IGBTs)
  - ✓Static Induction Transistors (SITs)

Bipolar Junction Transistors (BJTs)



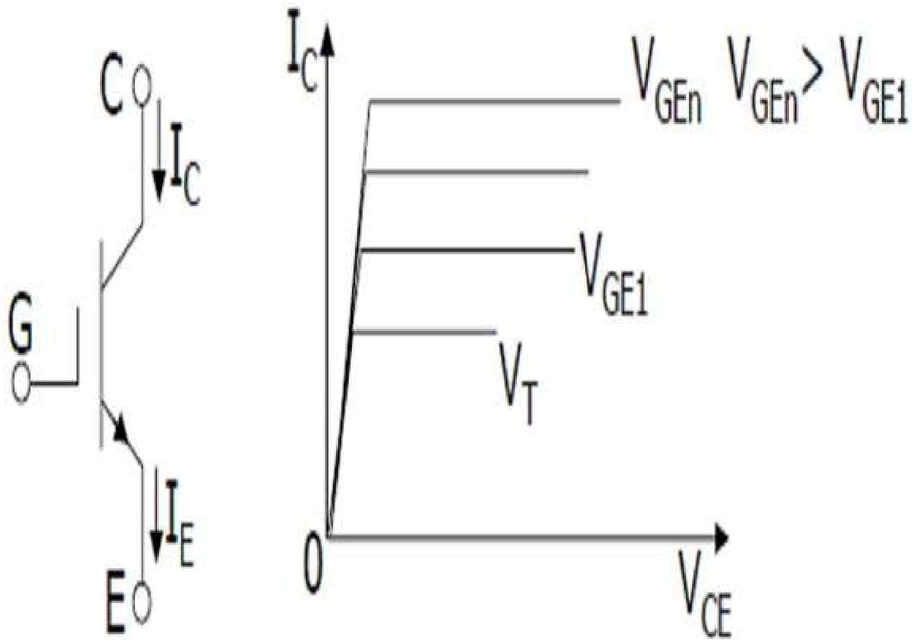
✓Used in power converters at frequency below 10 kHz
✓Power ratings up to 1200V, 400A.
✓VBE> 0, IB >ITH conduction (on) mode
✓VBE< 0, IB <ITH nonconduction (off) mode

➢ Power MOSFETs



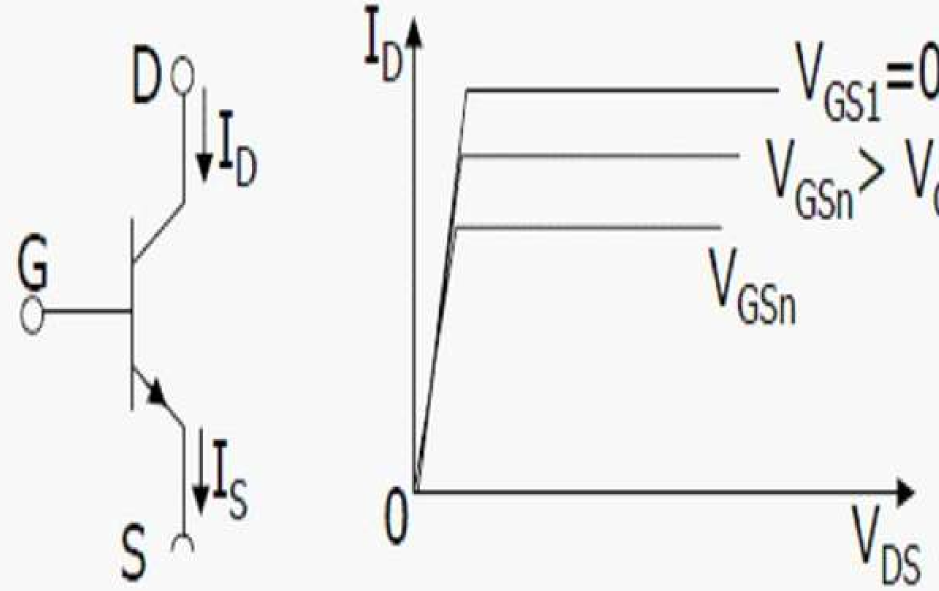
- ✓ Used in high-speed power converters at frequency range of several tens of kHz.
- ✓ Power ratings up to 1000V, 100A (relatively low power ratings).

➢ IGBTs



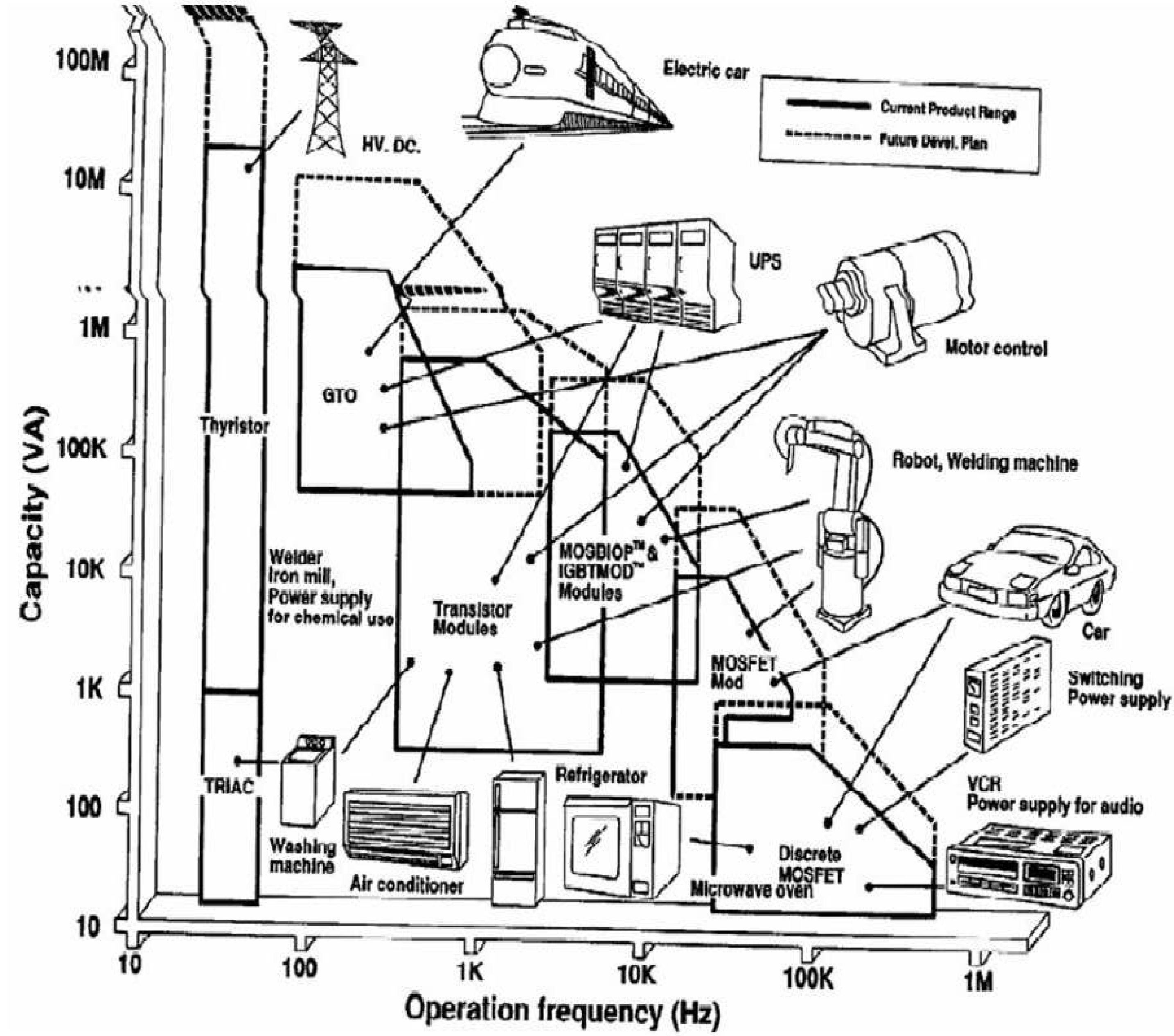
- ✓ Voltage controlled power transistors (better drive circuit) faster than BJTs but slower than MOSFETs.
- ✓ Used in power converters at frequency up to 20 kHz
- ✓ Power ratings up to 1700V, 2400A (high voltage high current).

➢ SITs



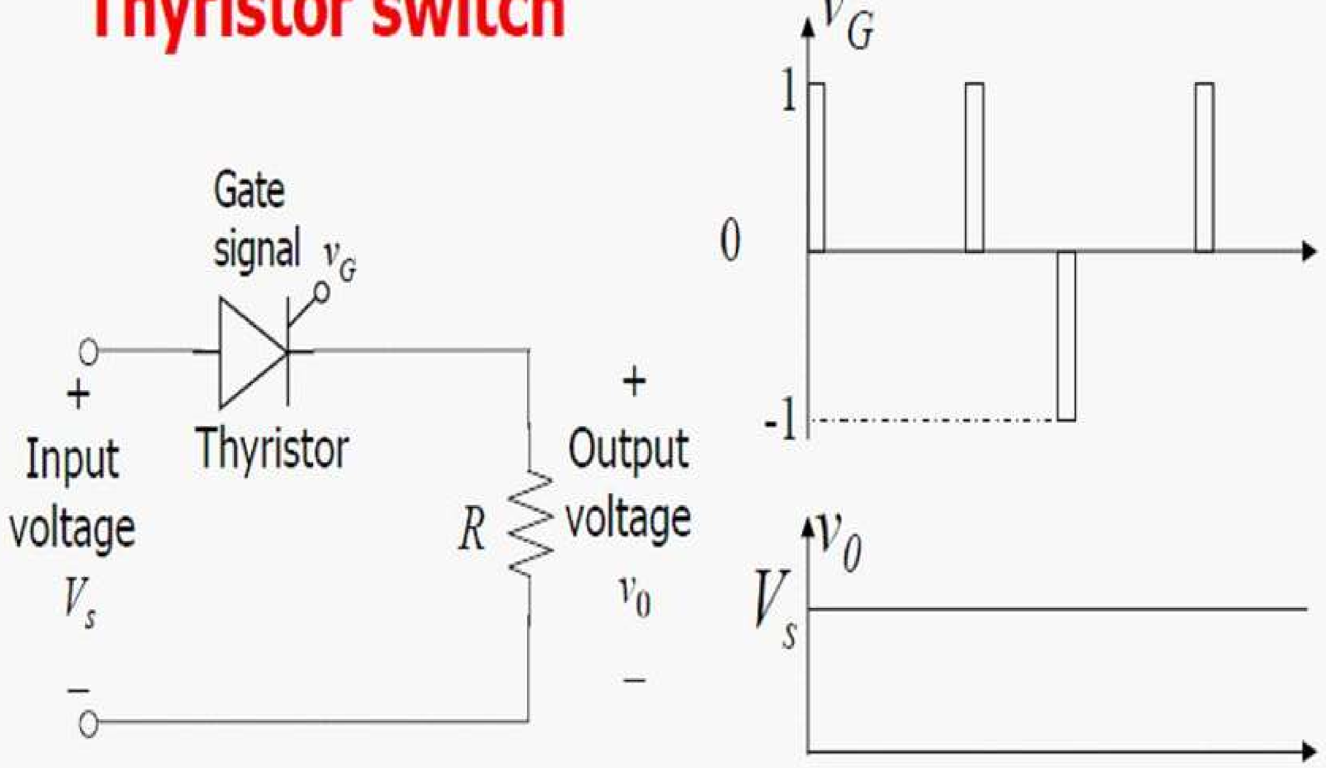
- ✓Used in high-power high frequency applications (audio, VHF/UHF, and microwave amplifiers)
- ✓Power ratings up to 1200V, 300A.
- ✓Has low-noise, low-distortion, high-audio-frequency power capability.
- ✓Very short turn-on and turn-off times (typically 0.25μs)
- ✓On-characteristic and high on-state drop limit its applications for general power conversions.

Power ranges of commercially available power semiconductor devices



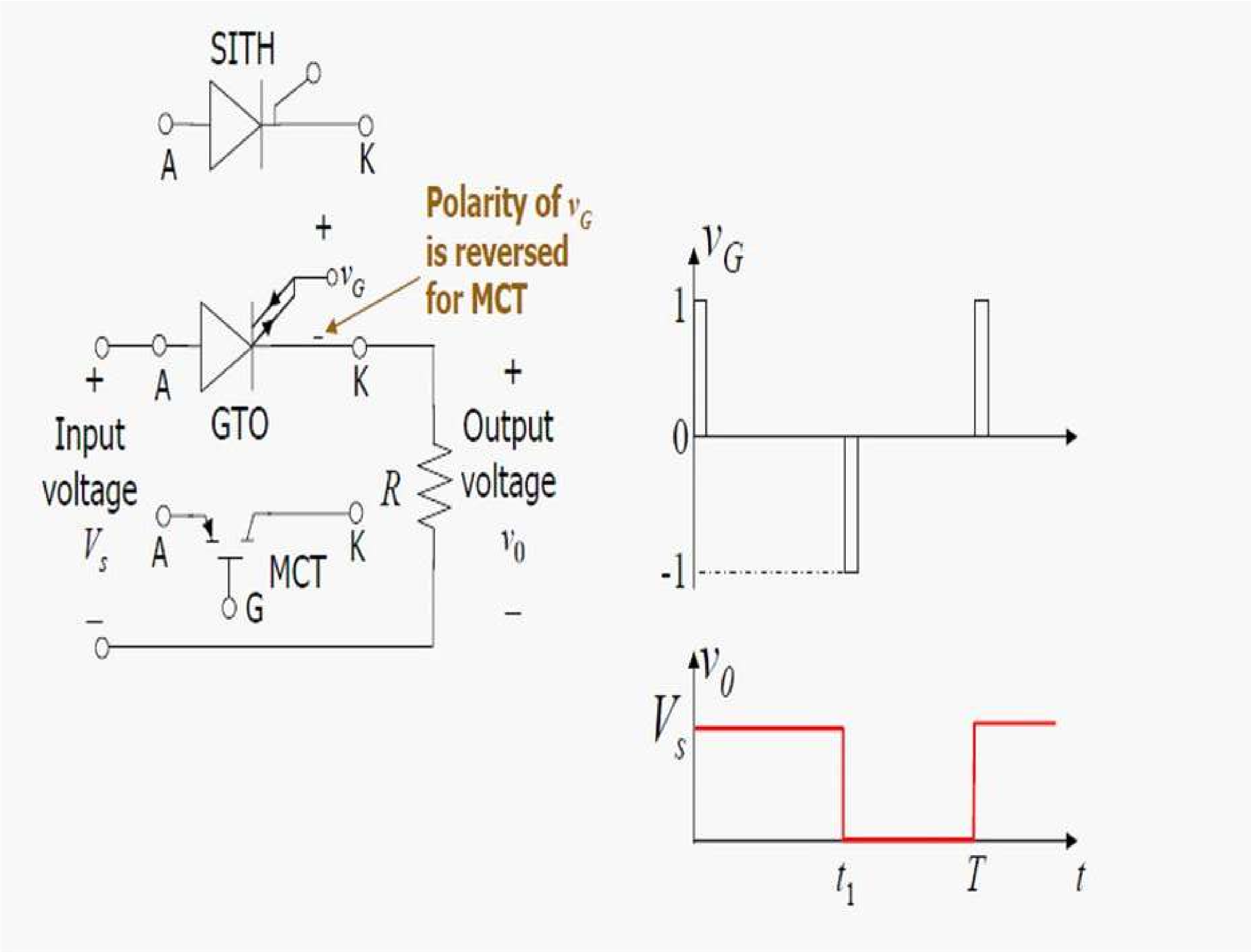
CONTROL CHARACTERISTICS OF POWER DEVICES

Thyristor switch



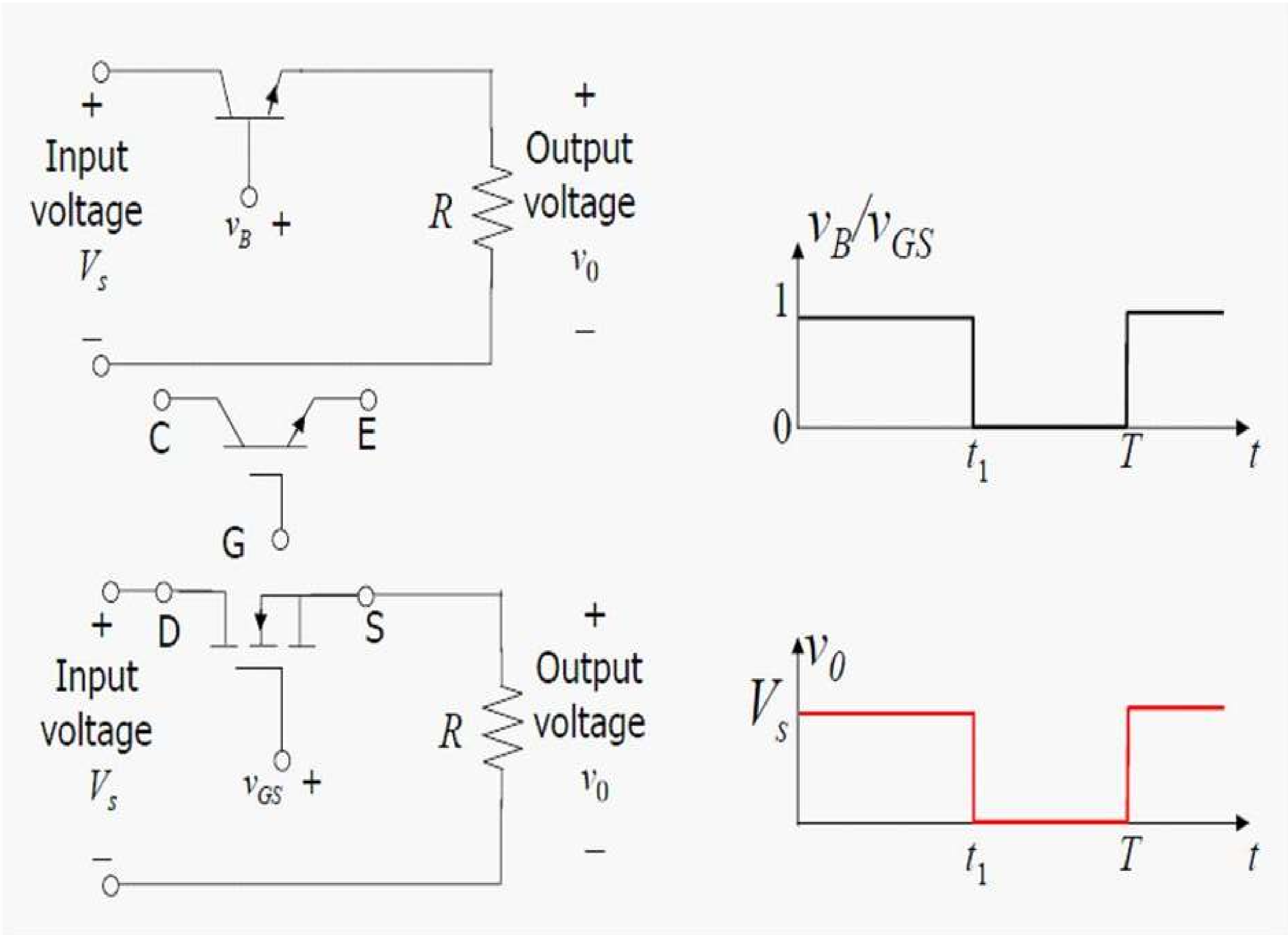
First pulse turns it on and stays always on

GTO/MTO/ETO/IGCT/MCT/SITH switch



Positive pulse turns them on and negative pulse turns them off

BJT/MOSFET/IGBT switch

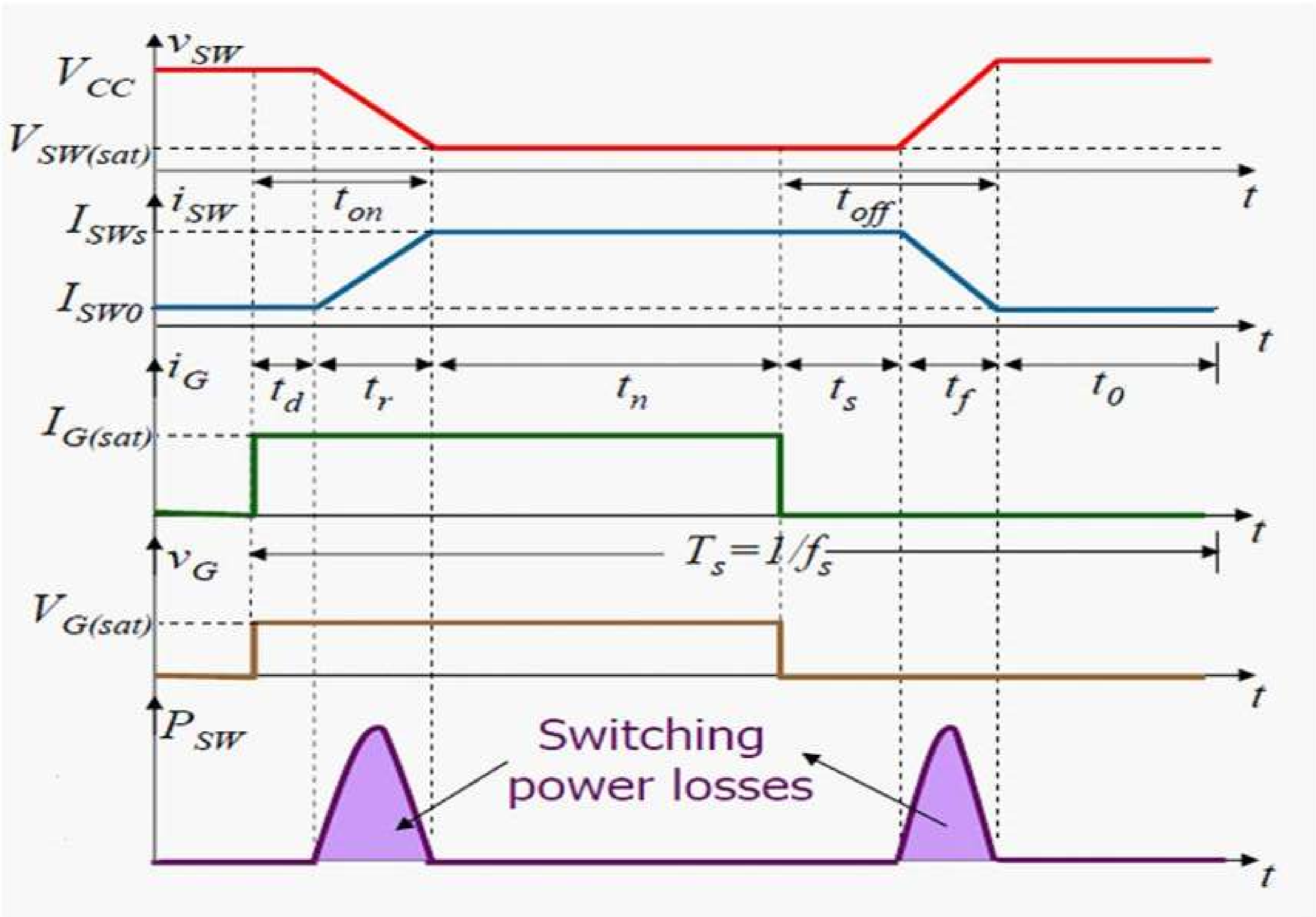


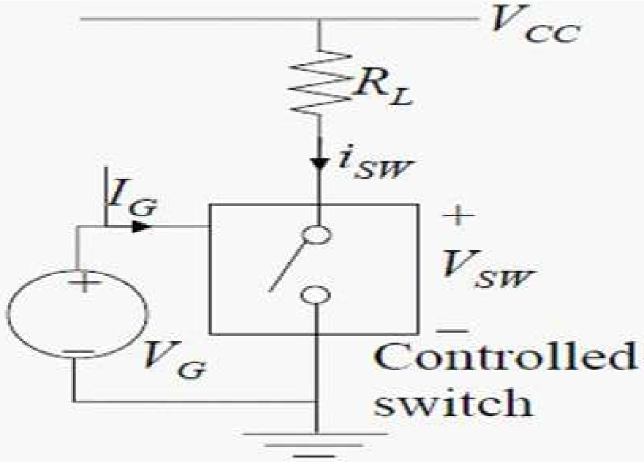
Positive voltage turns them on and zero voltage turns them off

Classification

1. Uncontrolled turn on and turn off (e.g. diode)
2. Controlled turn on and uncontrolled turn off (e.g. SCR)
3. Controlled turn on and off (e.g. BJT, MOSFET, IGBT, GTO, SITH, SIT, MCT)
4. Continuous gate signal requirement (e.g. BJT, MOSFET, IGBT, SIT)
5. Pulse gate requirement (e.g. SCR, GTO,MCT)
6. Bipolar voltage-withstanding capability (e.g. SCR, GTO)
7. Unipolar voltage-withstanding capability (e.g. BJT, MOSFET,GTO, IGBT, MCT)
8. Bidirectional current capability (e.g. TRIAC, RCT)
9. Unidirectional current capability (e.g. SCR, GTO, BJT, MOSFET, MCT,IGBT, SITH, SIT, Diode)

Practical Devices





$$P_{ON} = \frac{1}{T_s} \int_0^{t_{ON}} p\,dt$$

$$P_{SW} = f_s \left(\int_0^{t_r} p\,dt + \int_0^{t_s} p\,dt + \int_0^{t_f} p\,dt \right)$$

$$P_D = P_{ON} + P_{SW} + P_G$$

Conduction power losses | Switching power losses | Gate-driver power

Switch Specifications

- ➢ Voltage ratings
- ✓ Forward & reverse repetitive peak voltages
- ✓ On-state forward drop-voltage drop
- ➢ Current ratings
- ✓ Average,
- ✓ rms,
- ✓ repetitive peak,
- ✓ nonrepetitive peak,
- ✓ off-state leakage
- ➢ Switching speed or frequency
- ➢ di/dt
- ➢ dv/dt
- ➢ Switching losses
- ➢ Gate drive requirements
- ➢ Safe operating area (SOA): limits on the allowable steady-state operating points in the v-I coordinates
- ➢ Temperatures
- ➢ Thermal resistance

Device Choices

- Non of the existing switching devices is ideal.
- For high power applications from the ac 50- 60Hz main supply, phase control and bidirectional thyristors are the most economical choices.
- COOLMOS and IGBTs are potential replacements for MOSFETS and BJTs, respectively, in low and medium power applications.
- GTOs and IGCTs are most suited for high-power applications requiring forced commutation.
- With the increased advances in technology, IGBTs are increasingly employed in high-power applications and MCTs may find potential applications that require bidirectional blocking voltages.

DESIGN OF POWER ELECTRONICS EQUIPMENT

1. Design of power circuits
2. Protection of power devices
3. Determination of control strategy
4. Design of logic and gating circuits

- ✓ In this course, power devices are assumed ideal switches unless stated otherwise.
- ✓ Effect of stray inductance, circuit resistances, and source inductance are usually neglected.
- ✓ Before prototype is built, the designer should investigate the effects of the circuit parameters and device imperfections. The design should be modified if necessary.
- ✓ Only after the prototype is built and tested, the designer can be confident about the validity of the design proposed and can estimate more accurately some circuit parameters (e.g. stray inductance).

RMS VALUES OF WAVEFORMS

- rms values of current waveforms must be known:
  - ✓ To accurately determine losses in a device
  - ✓ To accurately determine current ratings of the device and components
- Current waveforms are rarely sinusoids or rectangles

$$I_{rms} = \sqrt{\frac{1}{\underbrace{T}_{\text{Time period}}}\int_0^T i^2\,dt}$$

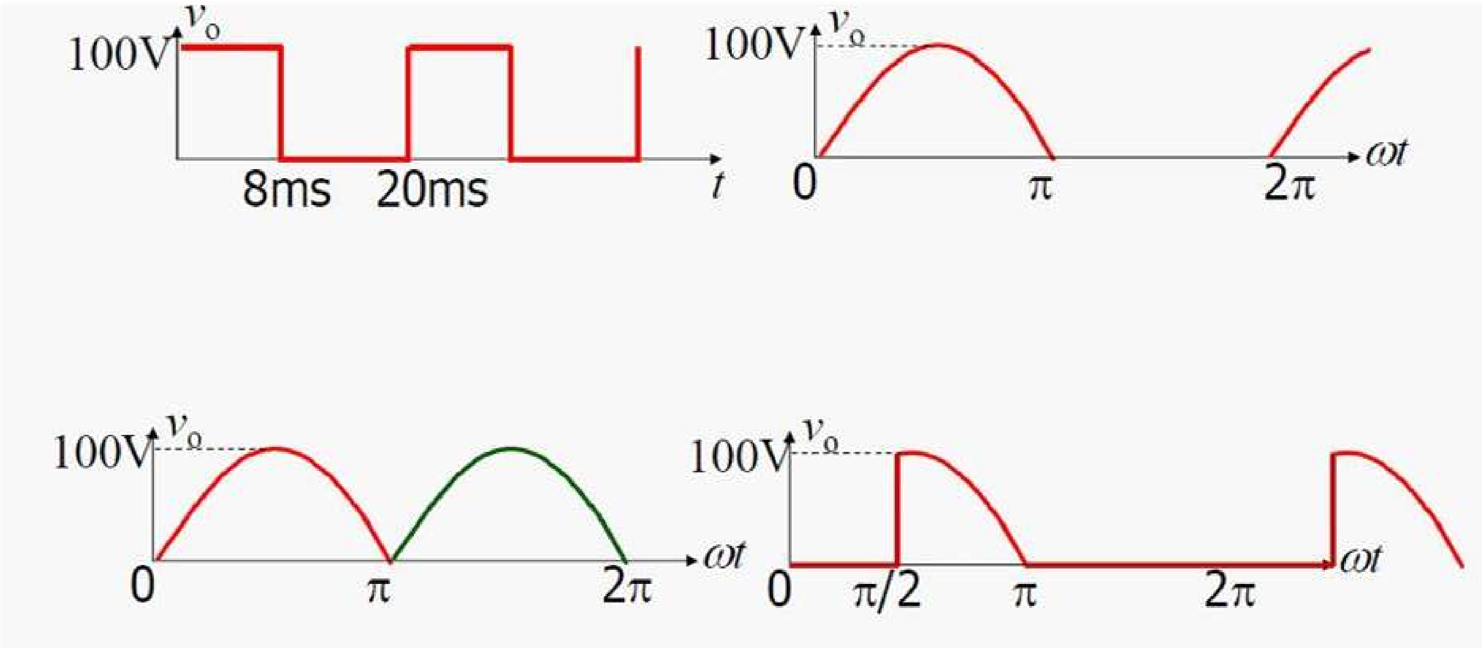
See page 25 (Fig. 1.17) for some rms values of commonly encountered waveforms

If a waveform can be broken into harmonics whose rms values can be calculated individually, the rms value of the actual waveform can be approximated satisfactory as:

$$I_{rms} = \sqrt{\underbrace{I_{dc}^2}_{\text{dc component}} + \underbrace{I_{rms(1)}^2 + I_{rms(2)}^2 \cdots + I_{rms(n)}^2}_{\text{Harmonics rms values}}}$$

Problems Solving:

Find the average and rms values of the following waveforms.

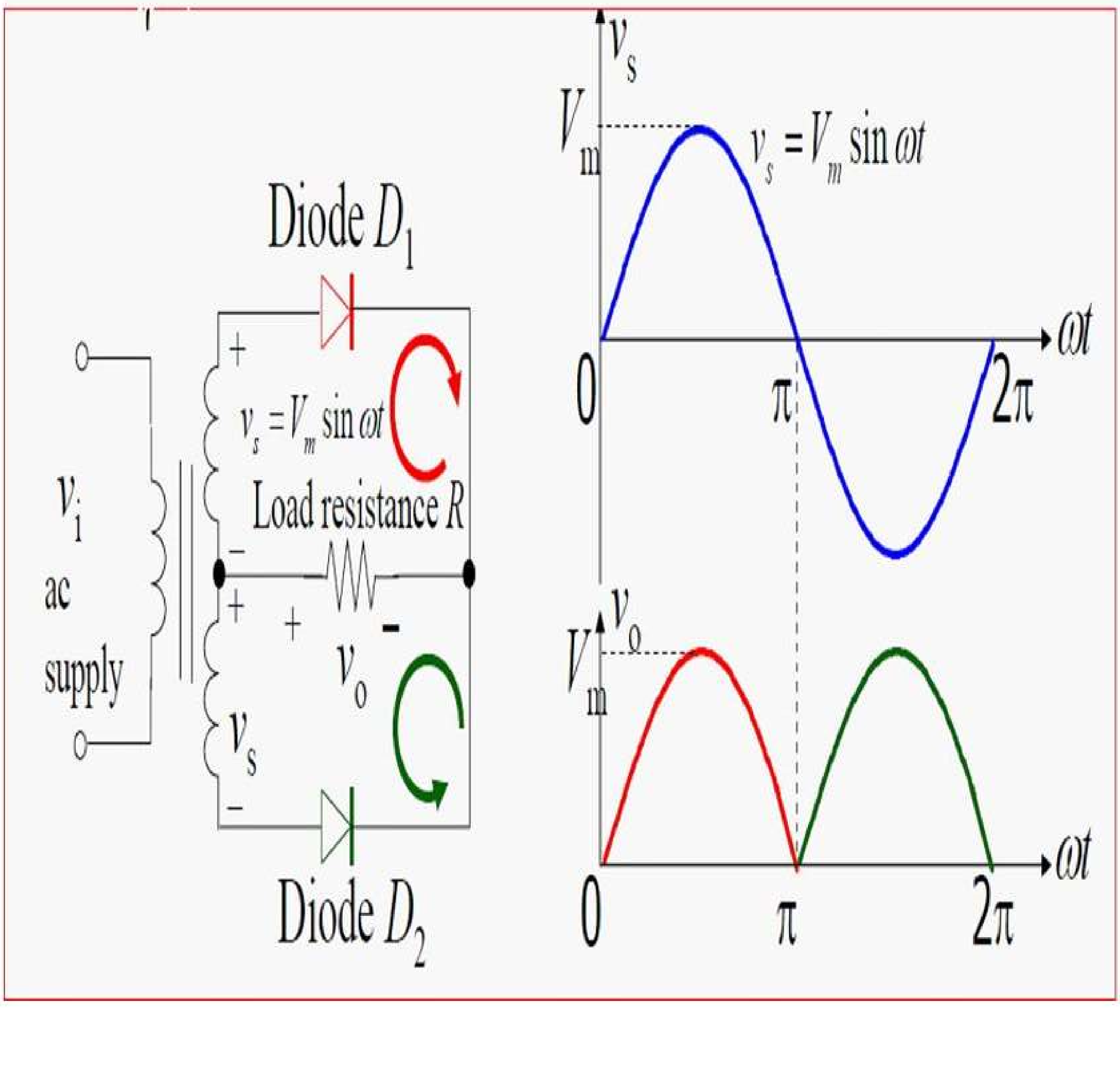


TYPES OF POWER ELECTRONIC CIRCUITS

- Diode rectifiers
- Ac-dc converters (controlled rectifiers)
- Ac-ac converters (ac voltage controllers)
- Dc-dc converters (dc choppers)
- Dc-ac converters (inverters)
- Static switches (ac or dc)

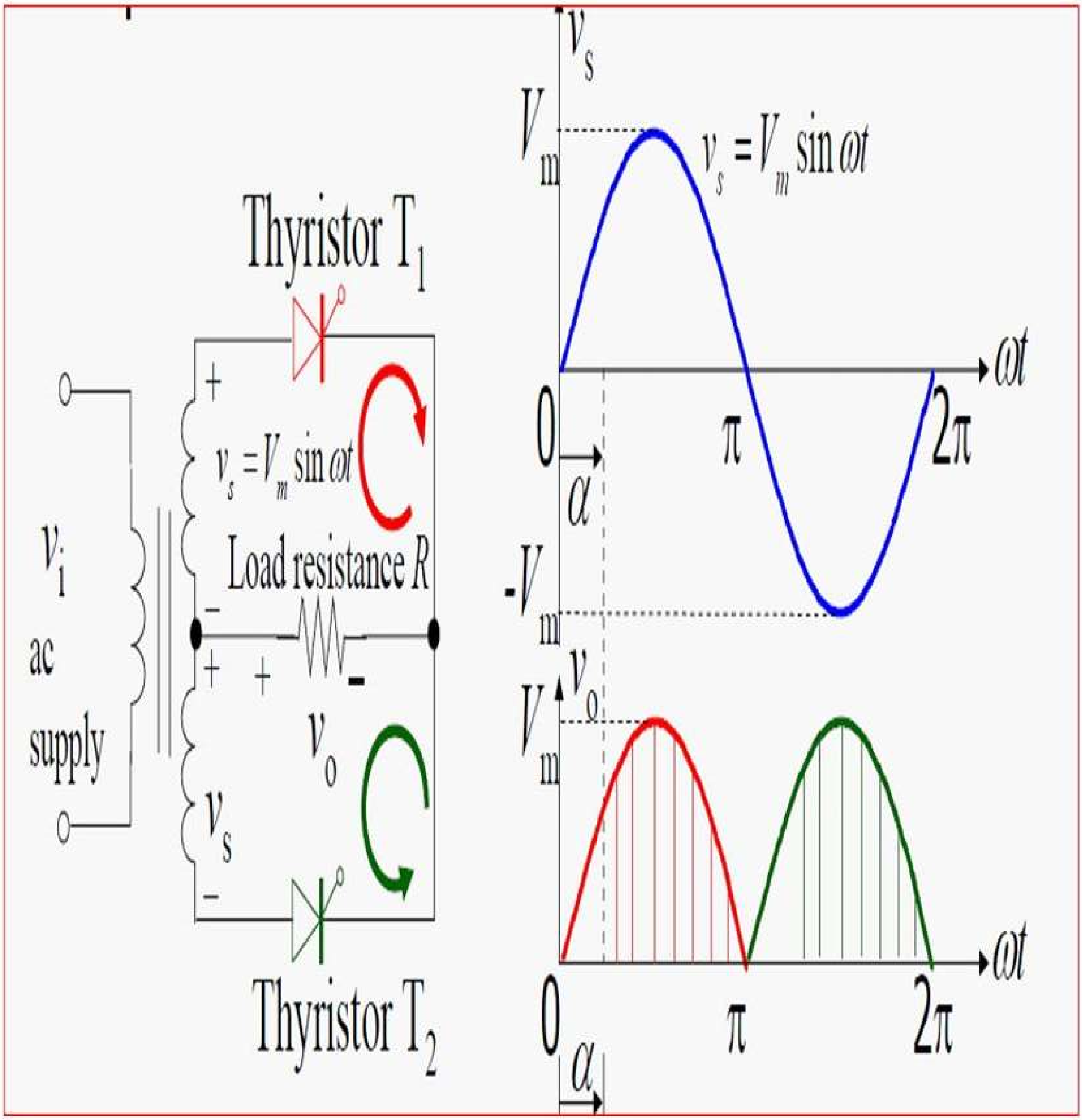
Diode rectifiers

- Converts ac into a fixed dc voltage.
- Input could be either single phase or three phase



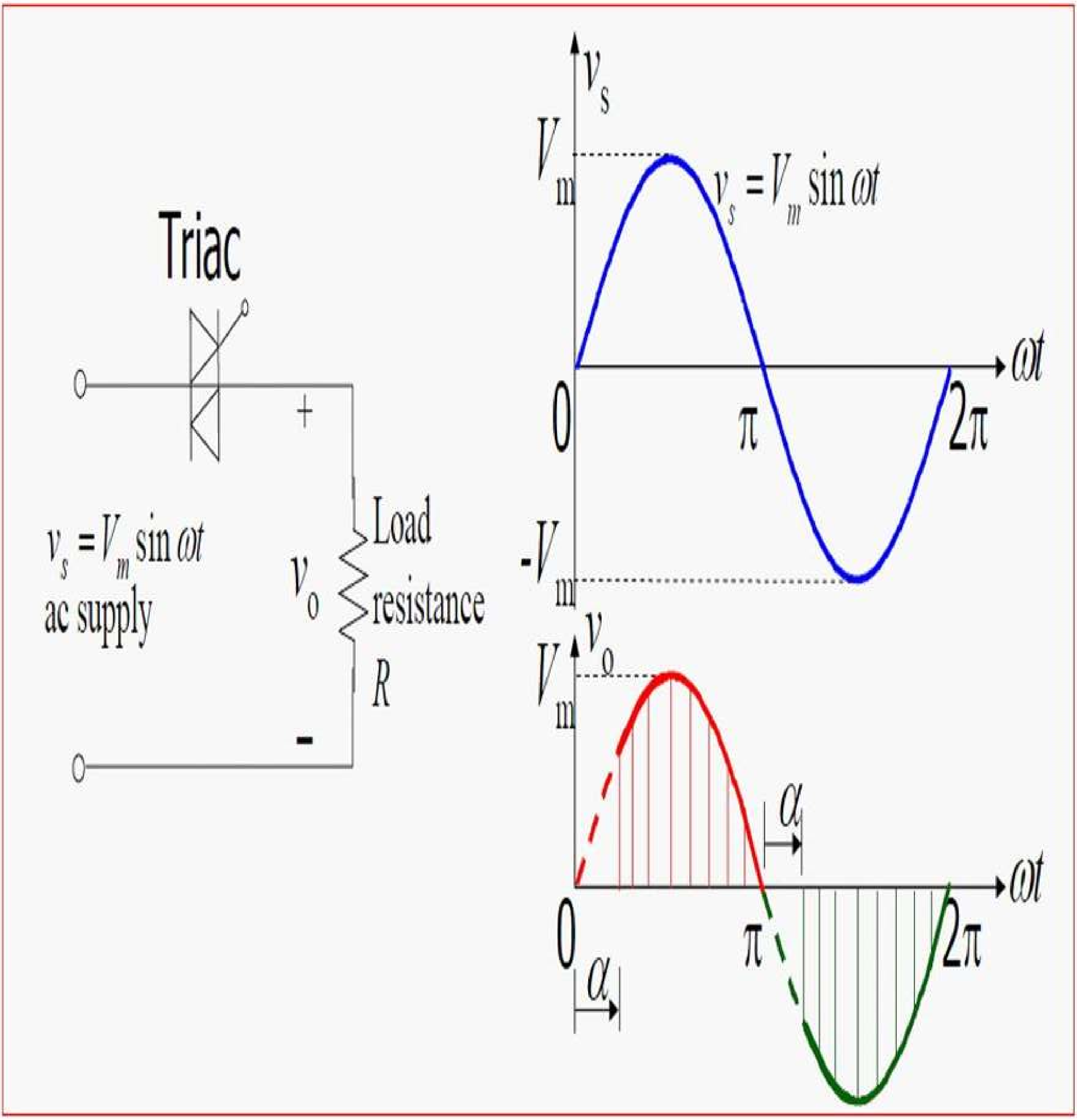
Ac-dc converters

- Converts ac into a variable dc voltage.
- Input could be either single phase or three phase



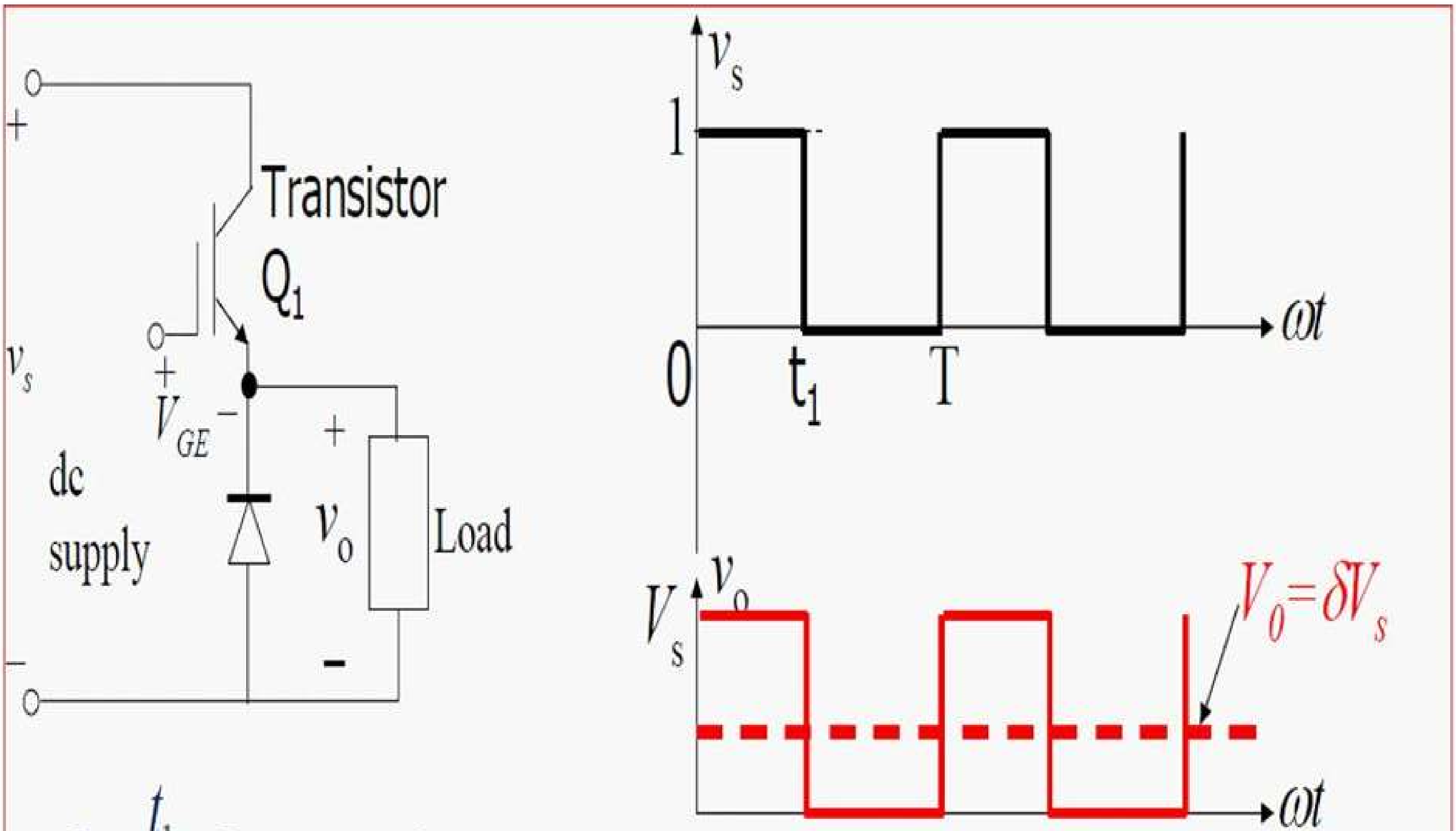
Ac-ac converters

- Converts fixed ac into a variable ac voltage.
- Input could be either single phase or three phase



Dc-dc converters (Choppers)

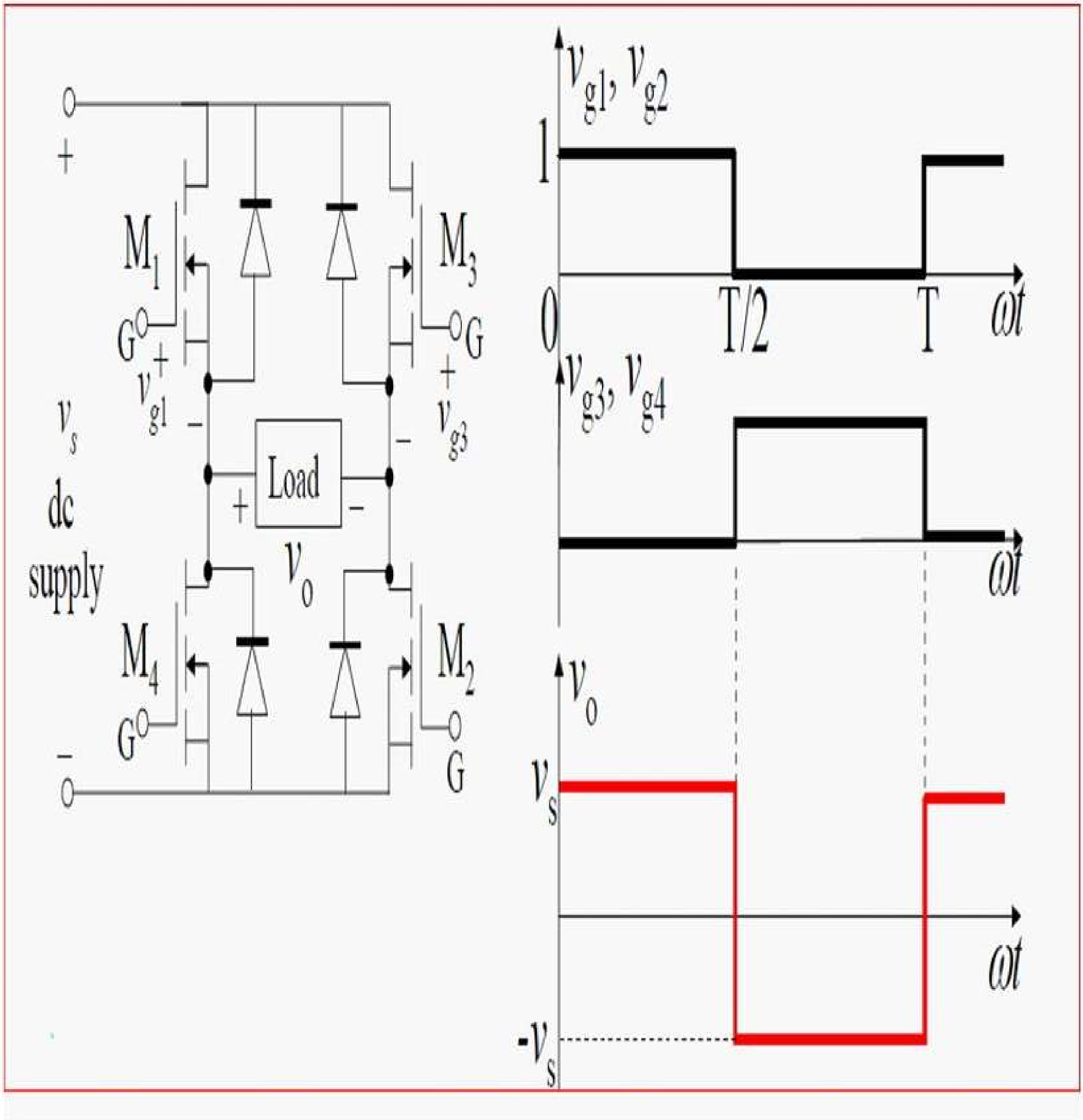
- Converts fixed dc into a variable dc voltage.



$$\delta = \frac{t_1}{T}$$ Duty cycle

Dc-ac converters (Inverters)

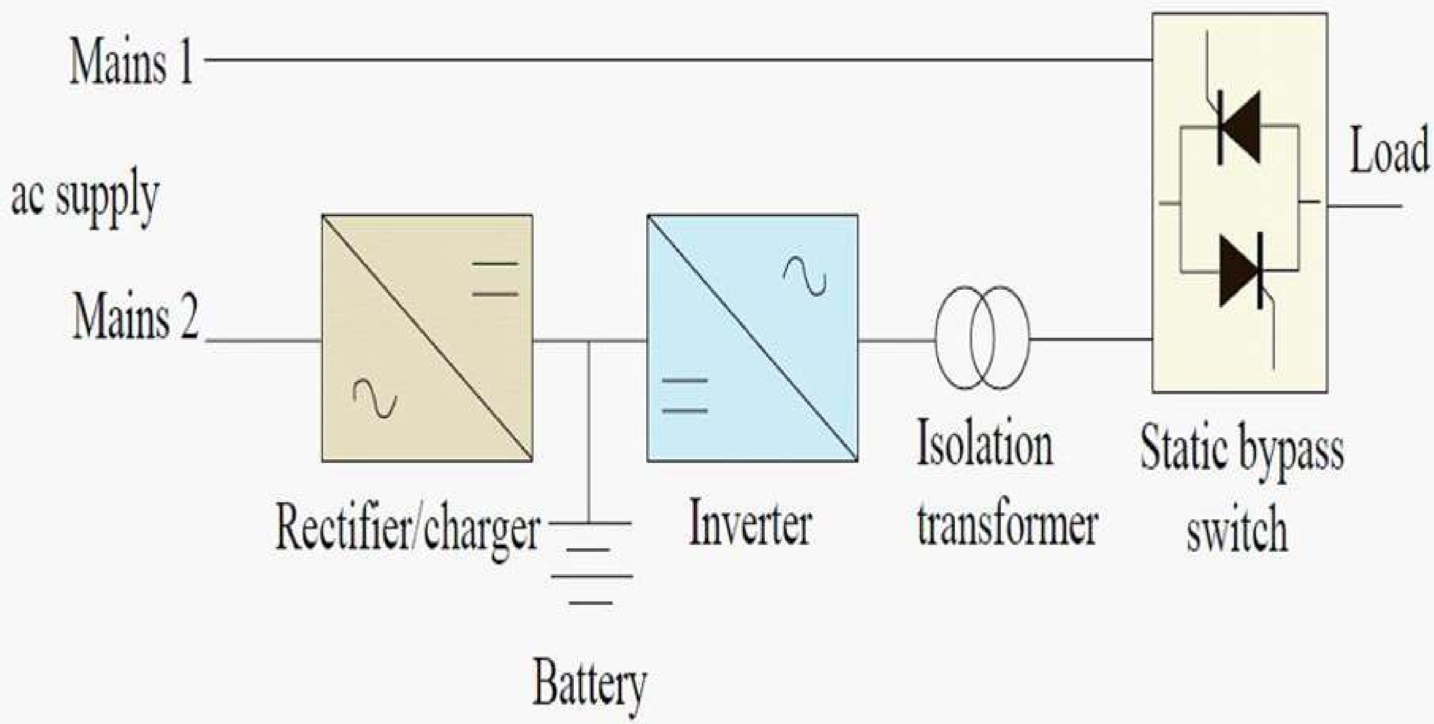
- Converts fixed dc into a variable ac voltage.
- Output can be single phase or three phase



Static switches

- Power electronic devices can operate as static switches or contactors to transmit either ac or dc power to loads.

Example: Uninterruptible Power Supply (UPS)



PERIPHERIAL EFFECTS (Effects of Power Converters)

Problems:

- Introduce current and voltage harmonics into the supply system and on converters output.
- Distortion of the output voltage.
- Harmonic generation into supply system
- Interference with communication and signaling circuits

Solutions:

- It is normally necessary to introduce filters in the input and output of a converter system to reduce the harmonic level to an acceptable magnitude.

Power quality issues

➢ Application of power electronics poses a challenge on the power quality issues and raises problems and concerns to be resolved by researchers.

➢ Important factors that measure the quality of a waveform are:

- Total harmonic distortion (THD)
- Displacement Factor (DF)
- Input power factor (IPF)

➢ Harmonic content of the waveforms is required to find these factors.

➢ To evaluate the performance of a converter, the input and output voltages and currents of a converter are expressed in a **Fourier series**.

➢ The **control strategy** of a power converter play an important part on the harmonic generation and output waveform distortion, and can be aimed to minimize or reduce these problems.

➢ Electromagnetic radiation and interference can be avoided by ***grounded shielding***.

POWER MODULES

- Power devices are available as a single unit or a module.
- A power converter often requires two, four, or six devices, depending on its topology.
- Power modules with dual (in half-bridge configuration), or quad (in full bridge) or six (in three phase) are available for almost all types of power devices.

- Modules offer the advantages of
  - lower on-state losses,
  - high voltage and current switching characteristics,
  - high speed (switching frequency)
- Some modules include transient protection and gate drive circuitry.
- Gate drive circuits are commercially available to drive individual devices or modules.

INTELLIGENT MODULES

- *Intelligent modules*, which are the state of the art of power electronics, integrate the power module and the peripheral circuit.
- Peripheral circuits consists of:
  - Input or output isolation from, and interface with, the signal and high-voltage system,
  - A drive circuit
  - Protection and diagnostic circuit
  - Microcomputer control
  - Control power supply
- Users need only to connect external (floating) power supplies.
- An intelligent module is also known as *smart power*.
- Smart power technology can be viewed as a box that interfaces power source to any load.
- These modules are used increasingly in power electronics.