Power Electronics

Roshan Alex
Assistant Professor
Department of Electrical Engineering
College of Engineering Trivandrum

Preamble: To impart knowledge about the power semiconductor devices, the operation of various power converters and its applications.

Prerequisite: Basics of Electrical Engineering / Introduction to Electrical Engineering/ Basics of Electronics Engineering

Course Outcomes: After the completion of the course the student will be able to:

CO 1	Explain the operation of modern power semiconductor devices and its characteristics.
CO 2	Analyse the working of controlled rectifiers.
CO 3	Explain the working of AC voltage controllers, inverters and PWM techniques.
CO 4	Compare the performance of different dc-dc converters.
CO 5	Describe basic drive schemes for ac and dc motors.

Syllabus

Module 1 - 11 hrs

Introduction to Power Electronics-Scope and applications-power electronics vs signal electronics (1 hr)
Structure and principle of operation ofpower devices- Power diode, Power MOSFET & IGBT – switching characteristics - comparison. Basic principles of wideband gap devices-SiC, GaN (4 hrs)
SCR- Structure, Static characteristics & Switching (turn-on & turn-off) characteristics - di/dt& dv/dt protection – Turn-on methods of SCR - Two transistor analogy (5 hr)

Gate triggering circuits – Requirements of isolation and synchronization in gate drive circuits- Opto and pulse transformer based isolation (1hr)

Module 2 - 9 hrs

Controlled Rectifiers (Single Phase) – Half-wave controlled rectifier with R load– Fully controlled and half controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – Output voltage equation- related simple problems(5 hrs)

Controlled Rectifiers (3-Phase) - 3-phase half-wave controlled rectifier with R load – Fully controlled & half-controlled bridge converter with RLE load (continuous conduction, ripple free) – Output voltage equation-Waveforms for various triggering angles (detailed mathematical analysis not required) (4 hrs)

Syllabus

Module 3 - 9 hrs

AC voltage controllers (ACVC) – 1-phase full-wave ACVC with R, & RL loads – Waveforms – RMS output voltage, Input power factor with R load (2 hrs)

Inverters – Voltage Source Inverters– 1-phase half-bridge & full bridge inverter with R and RL loads – THD in output voltage – 3-phase bridge inverter with R load – 120° and 180° conduction modes– Current Source Inverters-1-phase capacitor commutated CSI.(5 hrs)

Voltage control in 1-phase inverters – Pulse width modulation – Single pulse width, Multiple pulse width and Sine-triangle PWM (unipolar & bipolar modulation) – Modulation Index - Frequency modulation ratio.(2 hrs)

Module 4 - 8 hrs

DC-DC converters – Step down and Step up choppers – Single-quadrant, Two-quadrant and Four quadrant chopper – Pulse width modulation & current limit control in dc-dc converters. (4 hrs)

Switching regulators – Buck, Boost & Buck-boost –Operation with continuous conduction mode – Waveforms – Design of Power circuits (switch selection, filter inductance and capacitance) (4 hrs)

Syllabus

Module 5 - 11 hrs

Electric Drive: Introduction to electric drives – Block diagram – advantages of electric drives- types of load – classification of load torque (2 hrs)

DC Drives: Single phase semi converter and single phase fully controlled converter drives. Dual Converters for Speed control of DC motor-1-phase and 3-phase configurations; Simultaneous and Non-simultaneous operation. Chopper controlled DC drives- Single quadrant chopper drives- Regenerative braking control- Two quadrant chopper drives- Four quadrant chopper drives(6 hrs)

AC Drives: Three phase induction motor speed control. Stator voltage control – stator frequency control - Stator voltage and frequency control (v/f) (3 hrs)

Commonly used functions

	$-A$	$90 \pm A$	$180 \pm A$	$270 \pm A$	$360k \pm A$
sin	$-\sin A$	$\cos A$	$\mp \sin A$	$-\cos A$	$\mp \sin A$
cos	$\cos A$	$\mp \sin A$	$-\cos A$	$\pm \sin A$	$\cos A$

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\sin 2A = 2 \sin A \cos A$$

$$\cos 2A = 1 - 2\sin^2 A = 2\cos^2 A - 1$$

$$\sin A + \sin B = 2 \sin \frac{A+B}{2} \cos \frac{A-B}{2}$$

$$\sin A - \sin B = 2 \cos \frac{A+B}{2} \sin \frac{A-B}{2}$$

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$$\cos A - \cos B = 2 \sin \frac{A+B}{2} \cos \frac{B-A}{2}$$

$$\sin A \sin B = \frac{1}{2}[\cos(A-B) - \cos(A+B)]$$

$$\cos A \cos B = \frac{1}{2}[\cos(A-B) + \cos(A+B)]$$

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$$\int \sin nx\,dx = -\frac{\cos nx}{n}$$

$$\int \sin^2 nx\,dx = \frac{x}{2} - \frac{\sin 2nx}{4n}$$

Commonly used functions

$$\int \sin mx \sin nx \, dx = \frac{\sin(m-n)x}{2(m-n)} - \frac{\sin(m+n)x}{2(m+n)} \quad \text{for } m \neq n$$

$$\int \cos nx \, dx = \frac{\sin nx}{n}$$

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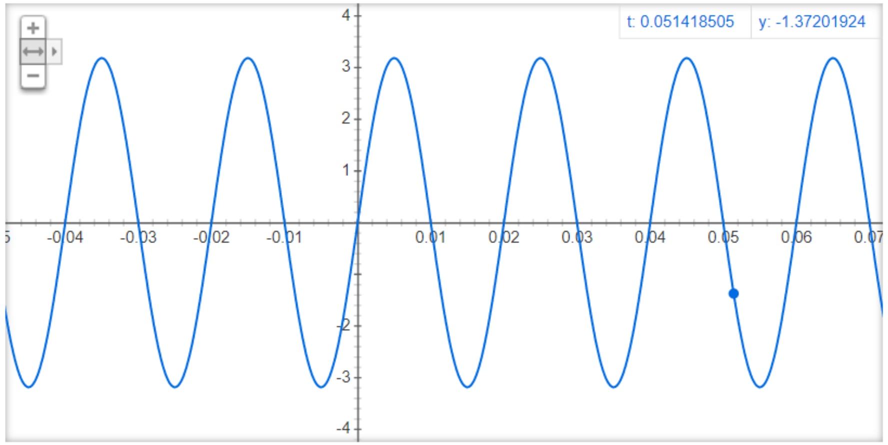
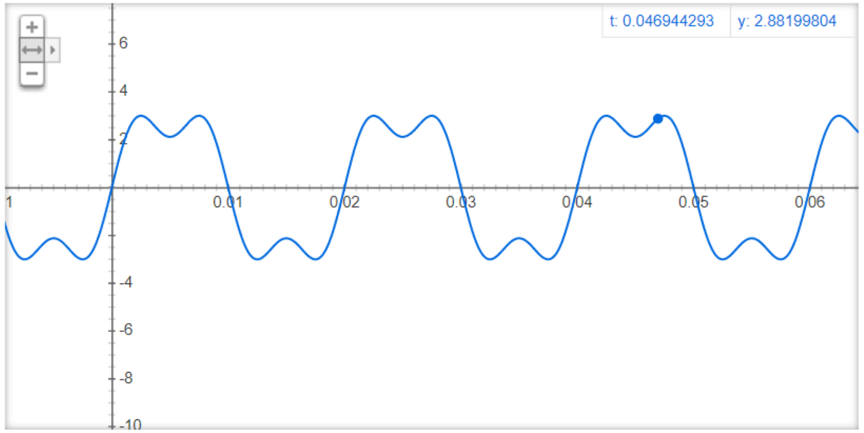
$$\int \sin nx \cos nx \, dx = \frac{\sin^2 nx}{2n}$$

$$\int \sin mx \cos nx \, dx = \frac{\cos(m-n)x}{2(m-n)} - \frac{\cos(m+n)x}{2(m+n)} \quad \text{for } m \neq n$$

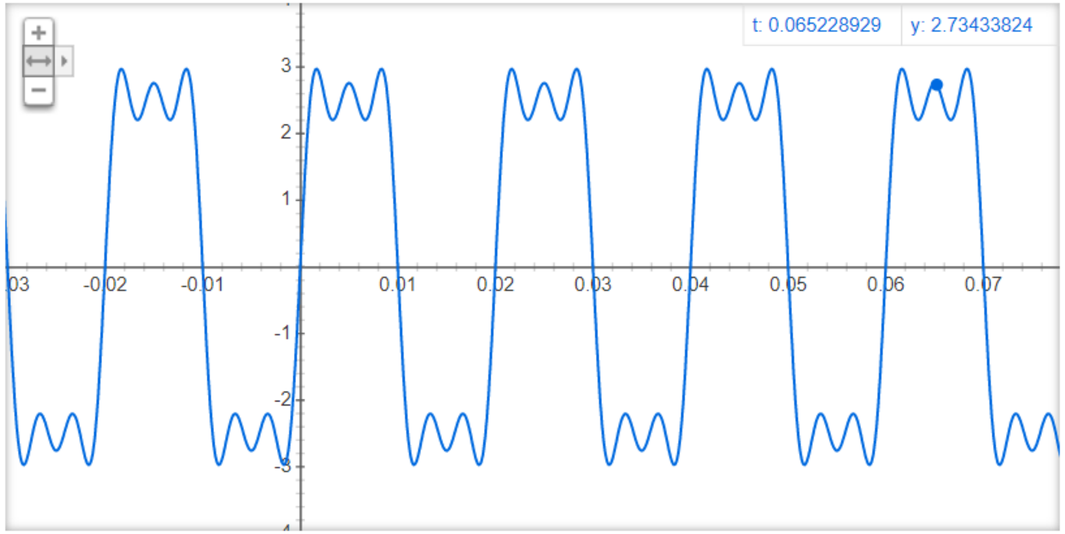
Graph for 10/π*sin(2*π*50*t)



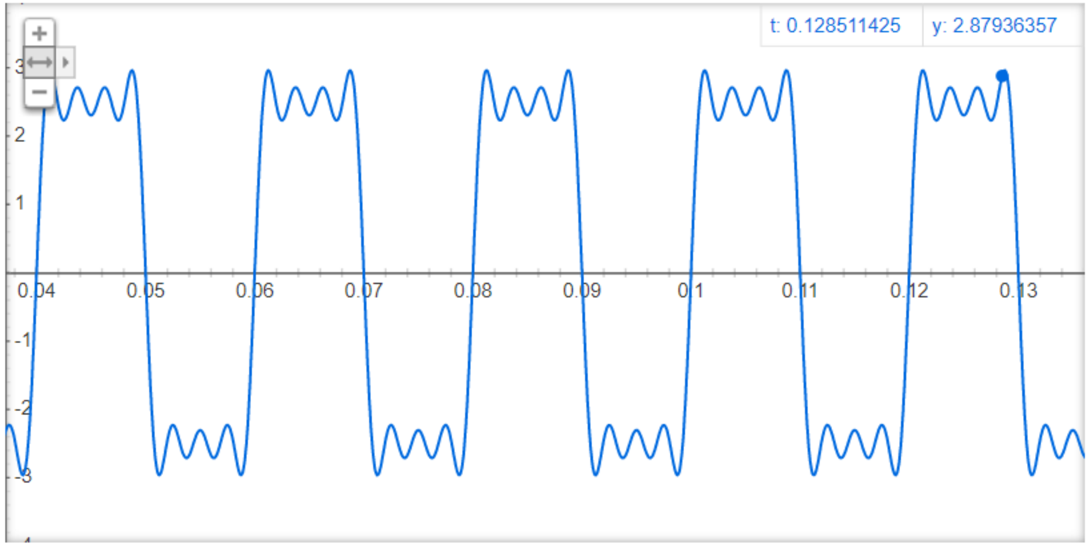
Graph for 10/π*sin(2*π*50*t)+10/(3*π)*sin(2*3*π*50*t)



Graph for 10/π*sin(2*π*50*t)+10/(3*π)*sin(2*3*π*50*t)+ 10/(5*π)*sin(2*5*π*50*t)

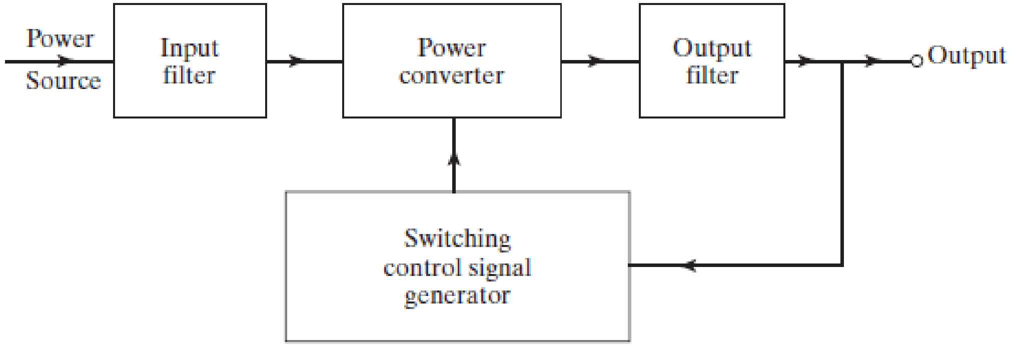


Graph for 10/π*sin(2*π*50*t)+10/(3*π)*sin(2*3*π*50*t)+ 10/(5*π)*sin(2*5*π*50*t)+10/(7*π)*sin(2*7*π*50*t)



Introduction

- Power electronics - power, electronics, and control
- Control deals with the steady-state and dynamic characteristics of closed-loop systems
- Power deals with the static and rotating power equipment for the generation, transmission, and distribution
- Electronics deal with the solid-state devices and circuits for signal processing to meet the desired control objectives
- *Power electronics*- application of solid-state electronics for the control and conversion of electric power
- Power electronics is based primarily on the switching of the power semiconductor devices



- Power-handling capability and the switching speed of the power devices
- development of power semiconductor technology, development of microprocessor, microcontroller, microcomputer technology
- power semiconductors regarded as the muscle, and microelectronics has the power and intelligence of a brain
- The first electronics revolution -1948 - invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain, and Shockley.
- The next breakthrough- 1956 - Bell Laboratories - invention of the *PNPN* triggering transistor, which was defined as a **thyristor** or **silicon-controlled rectifier (SCR).**
- silicon carbide (SiC) based power electronics is an alternative to state-of-the-art silicon (Si) technology
- Applications: variety of high-power products, heat controls, light controls, motor controls, power supplies, vehicle propulsion systems

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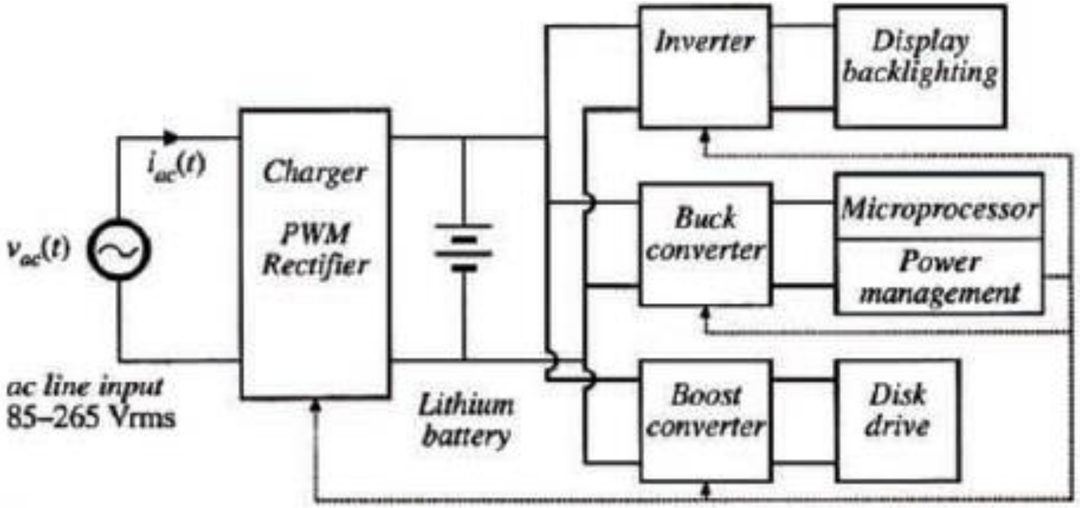
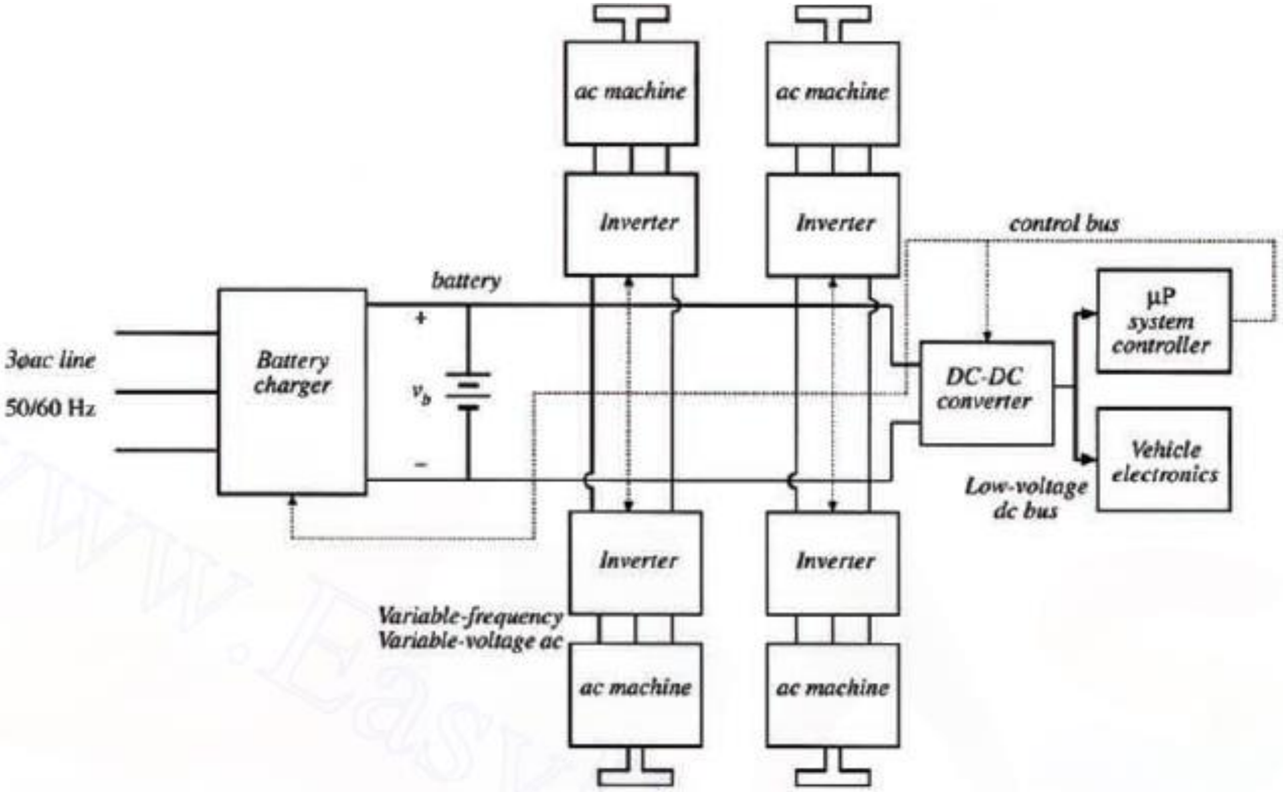
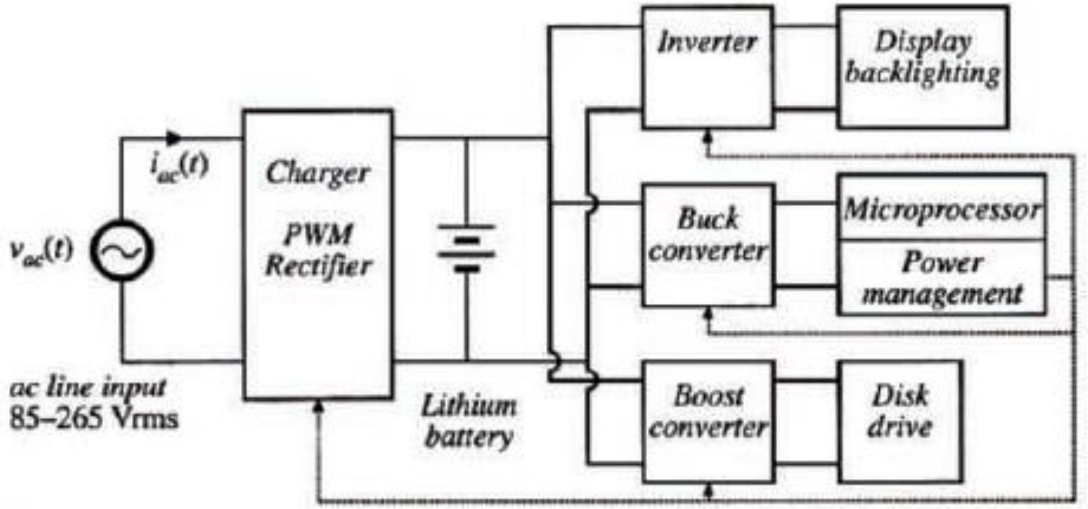
Applications

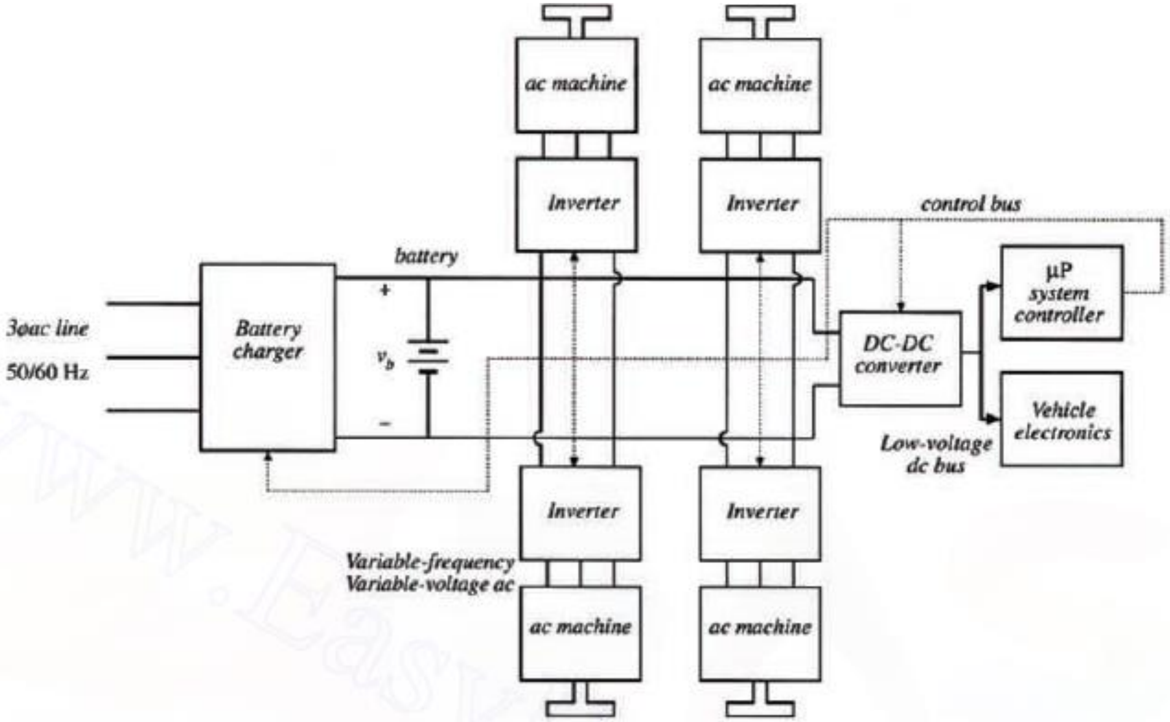




Applications



A laptop computer power supply system.



An electric vehicle power and drive system.

Types of Power Electronic Circuits

- The power electronics circuits can be classified into six types:

1. Diode rectifiers

2. DC–DC converters (dc choppers)

3. DC–AC converters (inverters)

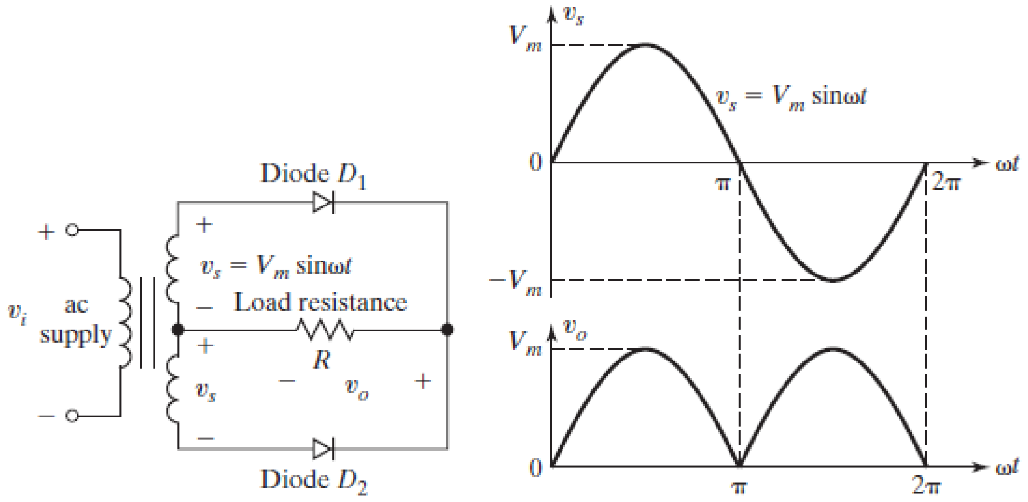
4. AC–DC converters (controlled rectifiers)

5. AC–AC converters (ac voltage controllers)

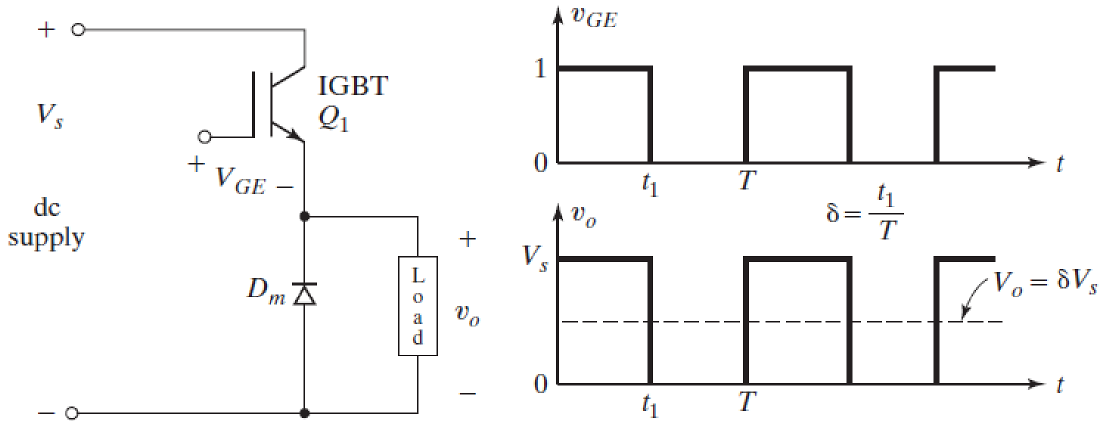
6. Static switches

Diode rectifiers

- A diode rectifier circuit converts ac voltage into a fixed dc voltage
- When its anode voltage > cathode voltage, the diode conducts and offers small voltage drop (0.7V)
- Diode behaves as an open circuit when its cathode voltage > anode voltage, offers high resistance (10 kΩ)
- The output voltage is a pulsating dc
- Input voltage to the rectifier could be either single phase or three phase



(a) Circuit diagram (b) Voltage waveforms



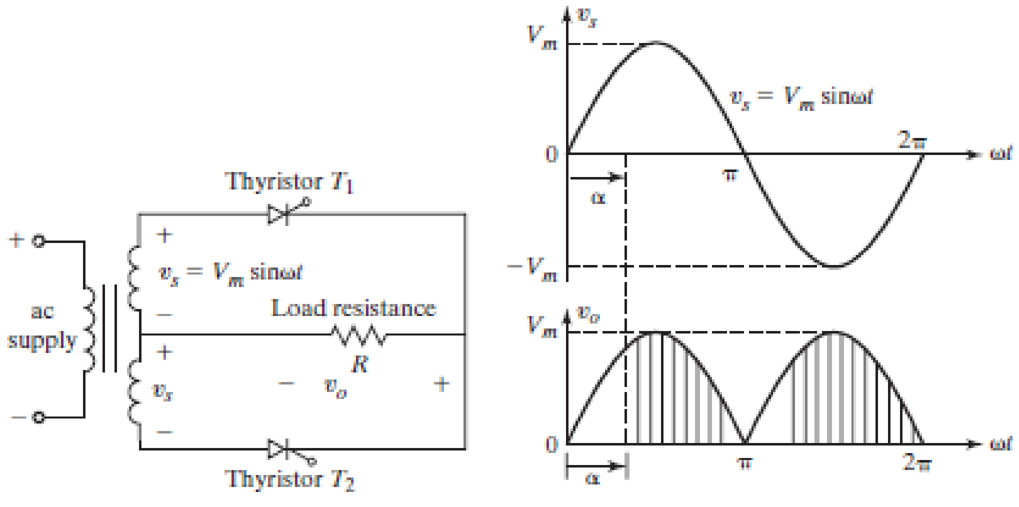
(a) Circuit diagram (b) Voltage waveforms

DC–DC converters.

- A dc–dc converter is also known as a **chopper** or switching regulator
- The average output voltage can be varied by controlling the duty cycle
- If T is the chopping period, then $t_1 = \delta T$ (δ = duty cycle of the chopper)
- The average output voltage becomes $V_{o(\mathrm{AVG})} = t_1 V_s / T = \delta\, Vs$
- Output voltage contains harmonics which could be filtered out
- Forced OR load commutation

AC-DC convertors

- Thyristor can be turned on by applying a gate pulse of approximately 10 V with a duration 100 μs
- The average value of the output voltage v_0 can be controlled by varying the conduction time of thyristors or firing delay angle, α.
- The input could be a single- or three-phase source. These converters are also known as *controlled rectifiers*.

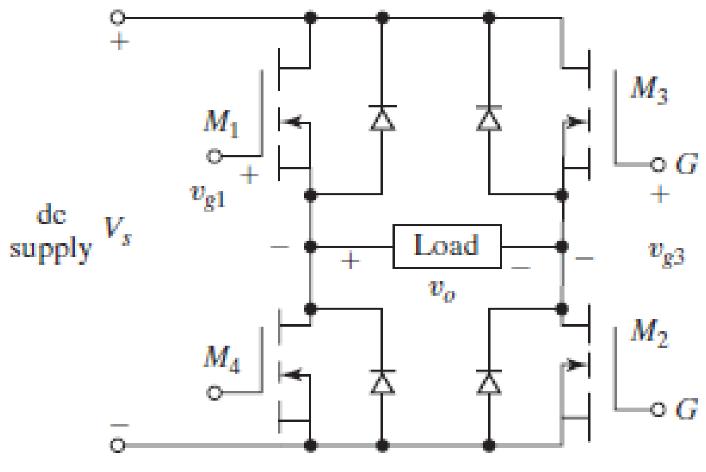


(a) Circuit diagram (b) Voltage waveforms

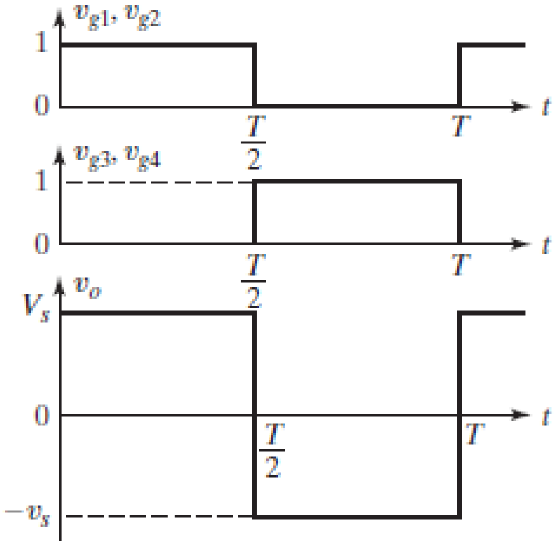
- These convert constant ac voltage to variable dc output voltage.
- These rectifiers use line voltage for their commutation - called **line commutated** / **naturally commutated** ac to dc converters

DC to AC converters (inverters)

- Converts fixed dc voltage to a variable ac voltage.
- The output may be a variable voltage and variable frequency.
- These converters use line, load or forced commutation for turning-off the thyristors.
- Applications: wide use in induction-motor and synchronous-motor drives, induction heating, UPS, HVDC transmission etc.
- Currently, conventional thyristors are also being replaced by GTOs in high-power applications and by power transistors in low-power applications.



(a) Circuit diagram

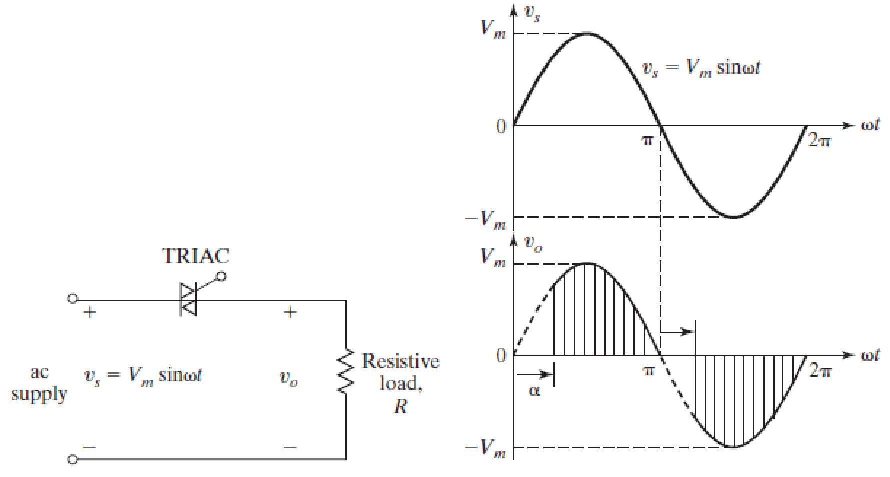


(b) Voltage waveforms

AC to AC converters

- Convert fixed ac input voltage into variable ac output voltage.

- These are of two types as under :



(a) Circuit diagram
(b) Voltage waveforms

(a) AC voltage controllers (AC voltage regulators):

- convert fixed ac voltage directly to a variable ac voltage at the same frequency.

- AC voltage controller employ two thyristors in antiparallel or a triac.

- Output voltage is controlled by varying the firing angle delay.

- Applications: lighting control, speed control of fans, pumps etc.

(b) Cycloconverters :

- convert input power at one frequency to output power at a different frequency through one-stage conversion

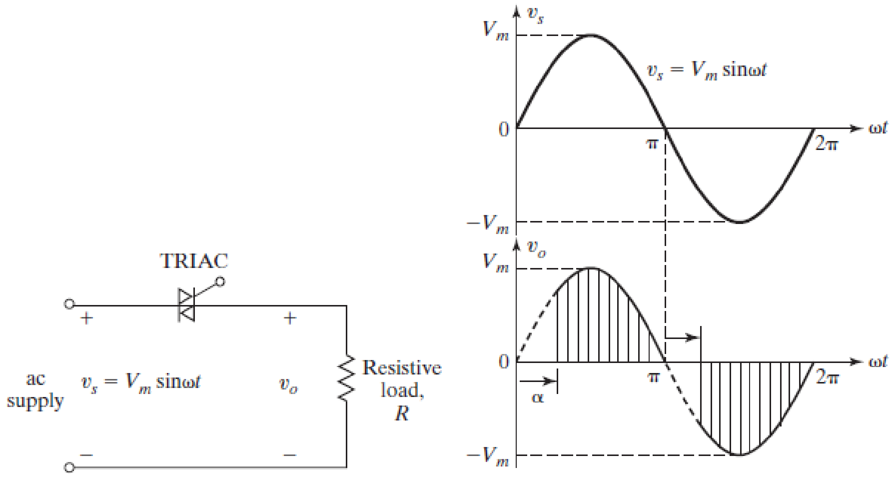
- These are primarily used for slow-speed large ac drives like rotary kiln

Static switches :

- The power semiconductor devices can operate as static switches or contactors

- possess many advantages over mechanical and electromechanical circuit breakers

- Depending upon the input supply, the static switches are called ac static switches or dc static switches.



(a) Circuit diagram
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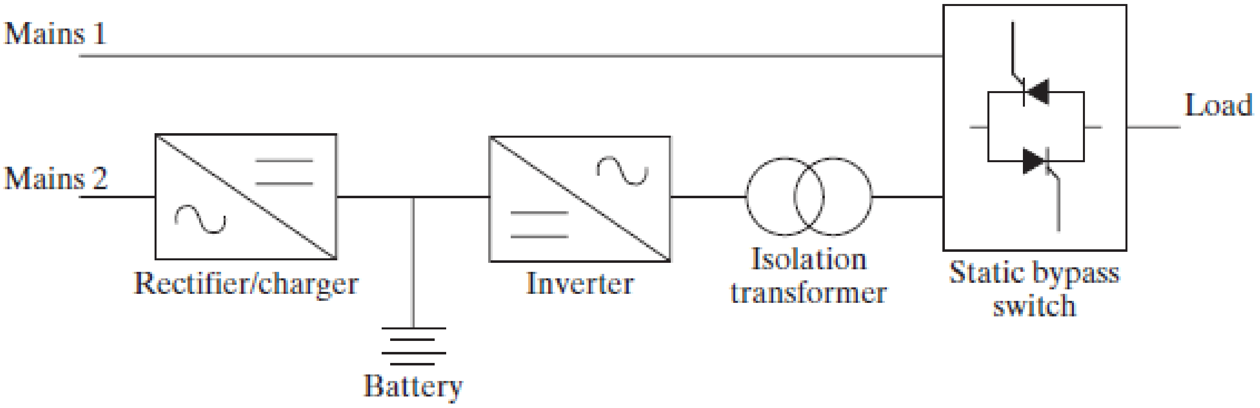


- Mains 1 supplies the normal ac supply to the load through the static bypass.
- The ac–dc converter charges the standby battery from mains 2.
- The dc–ac converter supplies the emergency power to the load through an isolating transformer.
- Mains 1 and mains 2 are normally connected to the same ac supply

Characteristics and Specifications of Switches

Characteristics of an ideal switch are as follows:

- During on-state,

(a) the ability to carry a high forward current I_F (tending to infinity)

(b) a low on-state forward voltage drop V_{ON} (tending to zero)

(c) a low on-state resistance R_{ON} (tending to zero)

(d) Low on-state power loss

- During off-state,

(a) the ability to withstand a high forward or reverse voltage V_{BR}, (tending to infinity)

(b) a low off-state leakage current I_{OFF}, (tending to zero)

(c) a high off-state resistance R_{OFF}, (tending to infinity)

(d) Low off-state power loss

- ability to sustain any fault current for a long time (high value of i^2t)

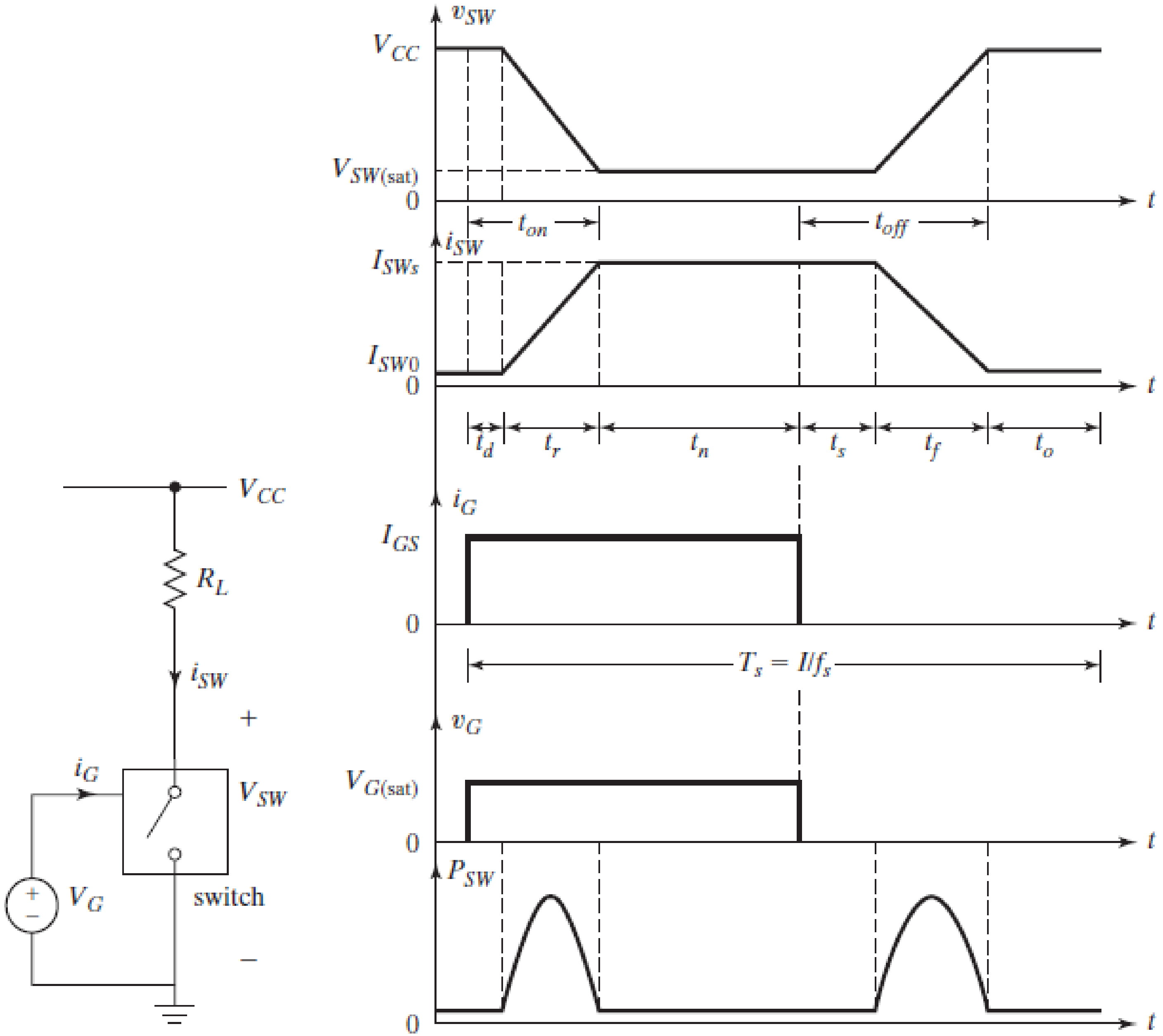
- turn on and off occurs instantaneously so that the device can be operated at high frequencies
- For turn-on and turn-off, it must require (a) low gate-drive power P_G (b) a low gate-drive voltage V_G (c) a low gate-drive current I_G
- Both turn-on and turn-off must be controllable
- For turning on and off, it should require a pulse signal only
- high *dv/dt rating* - the switch must be capable of handling rapid changes of the voltage across it
- high *di/dt rating* - the switch must be capable of handling a rapid rise of the current
- very low thermal impedance
- Negative temperature coefficient on the conducted current is required (results in equal current sharing when the devices are operated in parallel)

Characteristics of Practical Devices:

- During the turn-on and turn-off process- requires a finite time
- device current i_{sw} rises during turn-on, the voltage across the device v_{sw} falls
- device current falls during turn-off, the voltage across the device rises
- dissipates some energy when conducting and switching
- average conduction power loss P_{ON} is given by $P_{\mathrm{ON}} = \frac{1}{T_s}\int_0^{t_n} p\,dt$
- T_s denotes the conduction period and p is the instantaneous power loss
- Power losses increase during turn-on and turn-off as both the voltage and current have significant values

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

fs = 1/*Ts* is the switching frequency; ***td***, ***tr***, ***ts***, and ***tf*** are the delay time, rise time, storage time, and fall time,



(a) Controlled switch

(b) Switch waveforms

- Power dissipation of a switching device is given by: $P_D = P_{ON} + P_{SW} + P_G$
- On-state power P_{ON} and gate driver power P_G losses are generally low as compared to the switching loss P_{SW}
- P_G can be neglected
- total amount of energy loss = product of P_D and switching frequency f_S

Switch Specifications

Voltage ratings:

Forward and reverse repetitive peak voltages, and an on-state forward voltage drop.

Current ratings:

Average, root-mean-square (rms), repetitive peak, nonrepetitive peak, and off-state leakage currents

Switching speed or frequency:

- Transition from a fully nonconducting to a fully conducting state (turn-on) and from a fully conducting to a fully nonconducting state (turn-off) are very important parameters

$$f_s = \frac{1}{T_s} = \frac{1}{t_d + t_r + t_n + t_s + t_f + t_o}$$

- if $t_d = t_r = t_n = t_s = t_f = t_o = 1\mu s$, $T_s = 6\ \mu s$ and the maximum permission frequency is

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di/dt rating:

- If the current rises rapidly, the current flow may be concentrated to a certain area and the device may be damaged.
- The *di/dt* of the current through the device is normally limited by connecting a small inductor in series with the device (*series snubber)*

dv/dt rating:

- A semiconductor device has an internal junction capacitance C_J.
- Rapid switching can cause the current ($C_J\, dv/dt$) flowing through the device *to* be too high
- The *dv/dt* is limited by connecting an *RC* circuit across the device (*shunt snubber/ snubber)*

Switching losses:

- Simultaneous existence of high voltage and current in the device during switching results in high switching losses (often exceed on-state conduction losses)

Gate-drive requirements:

- The gate-drive voltage and current are important parameters to turn on and off a device.

- Affects losses and total equipment cost
- large and long current pulse requirements for turn-on and turn-off are not preffered

Safe operating area (SOA):

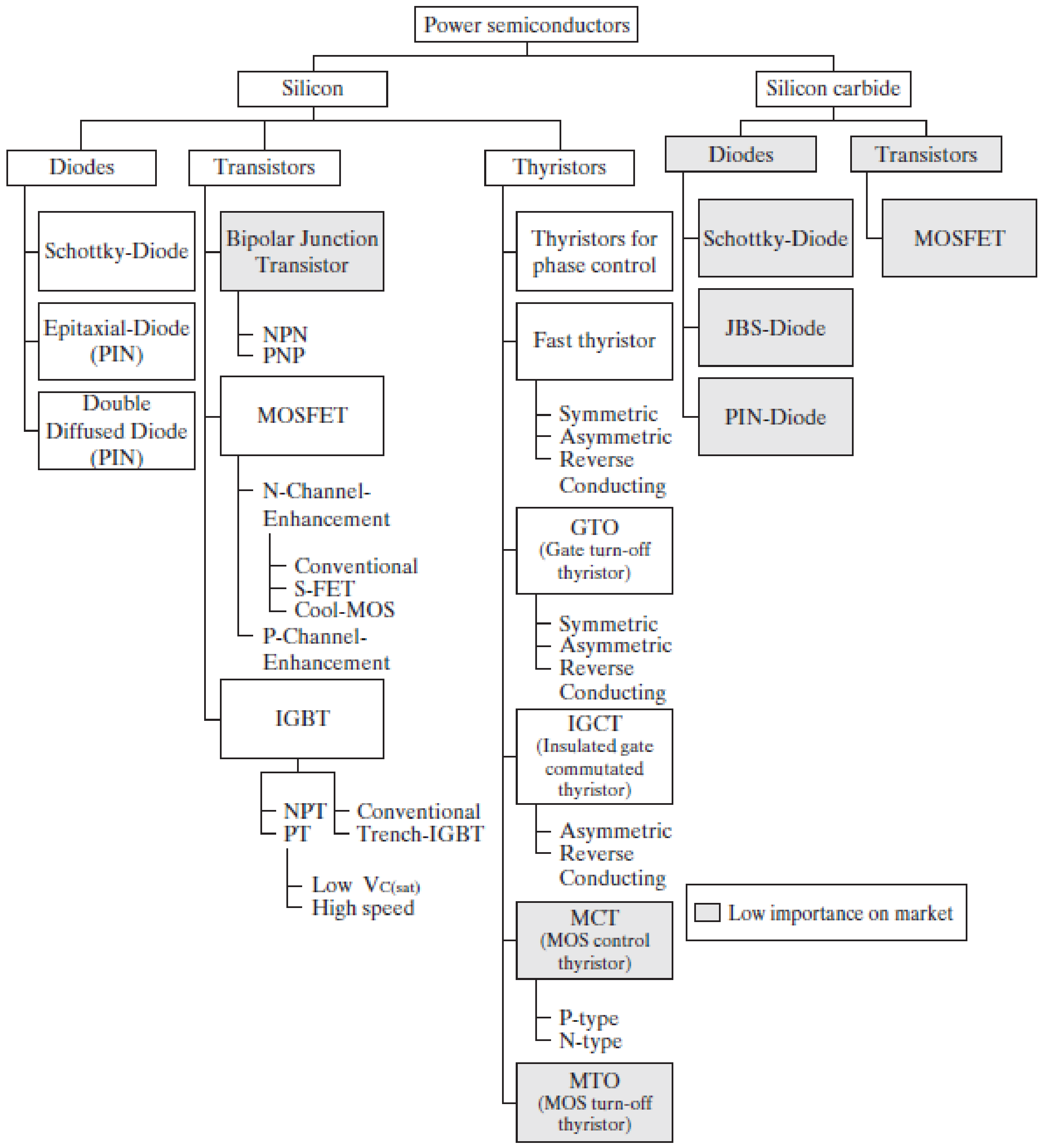
- The amount of heat generated in the device is proportional to the power loss
- For constant power rating, the current must be inversely proportional to the voltage
- SOA limits the allowable steady-state operating points in the voltage–current coordinates

The $\boldsymbol{I^2t}$ of the device must be less than that of the fuse so that the device is protected under fault current conditions.

Thermal resistance:

- Power dissipation must be rapidly removed from the internal wafer through the package and ultimately to the cooling medium.
- Power devices are generally mounted on heat sinks (removing heat is a costly affair)
- Junction-to-case thermal resistance, Q_{JC}; case-to-sink thermal resistance, Q_{CS}; and sink-ambient thermal resistance, $_{QSA}$

Power semiconductor devices



Control Characteristics of Power Devices

- Uncontrolled turn-on and turn-off (e.g., diode)
- Controlled turn-on and uncontrolled turn-off (e.g., SCR)
- Controlled turn-on and -off characteristics (e.g., BJT, MOSFET, GTO, SITH, IGBT, SIT, MCT);
- Continuous gate signal requirement (BJT, MOSFET, IGBT, SIT);
- Pulse gate requirement (e.g., SCR, GTO, MCT);
- Bipolar voltage-withstanding capability (SCR, GTO);
- Unipolar voltage-withstanding capability (BJT, MOSFET, GTO, IGBT, MCT);
- Bidirectional current capability (TRIAC, RCT);
- Unidirectional current capability (SCR, GTO, BJT, MOSFET, MCT, IGBT, SITH, SIT, diode).