Power Electronics

for

Electrical Engineering

By

THE GATE ACADEMY
A Forum of IIT / IISc Graduates

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Syllabus for Power Electronics

Characteristics of Semiconductor Power Devices: Diode, Thyristor, Triac, GTO, MOSFET, IGBT; DC to DC Conversion: Buck, Boost and Buck-Boost Converters; Single and Three Phase Configuration of Uncontrolled Rectifiers, Line Commutated Thyristor Based Converters, Bidirectional Ac to Dc Voltage Source Converters, Issues of Line Current Harmonics, Power Factor, Distortion Factor of Ac to Dc Converters, Single Phase and Three Phase Inverters, Sinusoidal Pulse Width Modulation.

Analysis of GATE Papers

Year	Percentage of Marks	Overall Percentage
2015	7.50	9.51%
2014	7.00	
2013	12.00	
2012	8.00	
2011	12.00	
2010	5.00	
2009	9.00	
2008	10.67	
2007	12.00	
2006	12.00	

Contents

“Picture yourself vividly as winning and that
alone will contribute immeasurably to success."

...Harry Fosdick

CHAPTER 1 Power Semiconductor Devices

Learning Objectives

After reading this chapter, you will know:

1. Basic Power Electronic Circuit Block Diagram
2. Freewheeling Diodes (Application of Power Diodes)
3. Power Transistors
4. Power MOSFET
5. Silicon Controlled Rectifier (SCR)
6. Thyristor Turn-On Methods
7. Switching Characteristics of Thyristor
8. Thyristor Commutation

Introduction

Power Engineering is about generation, transmission, distribution and utilization of electrical energy with high efficiency and is based on electromagnetic principles. Hence power devices have less life, more maintenance, slower dynamic response and smaller size but higher operating power. Electronics engineering is about transmission and reproduction of signals of lower power and is based on physical phenomena. Hence operating power in electronic circuits is lower but these circuits have higher efficiency and higher reliability. Hence power electronics, which is hybrid version of power engineering and electronics engineering, became popular and it uses physical phenomenon but these circuits are rated to operate at higher power. Hence power electronic circuits have higher efficiency, higher reliability and longer life. Also corresponding devices can be manufactured based on mass production and require less maintenance.

Definition:

It is a application which deals with efficient, conversion, control and conditioning of electrical power.

1. Conversion refers to the form of power:
   AC to AC, AC to DC, DC to AC, DC to DC
2. Control function with respect to:
   Voltage, Current, Frequency, Power, Power Factor
3. Conditioning may be to improve:
   Reliability, Wave Shape, Reactive Power

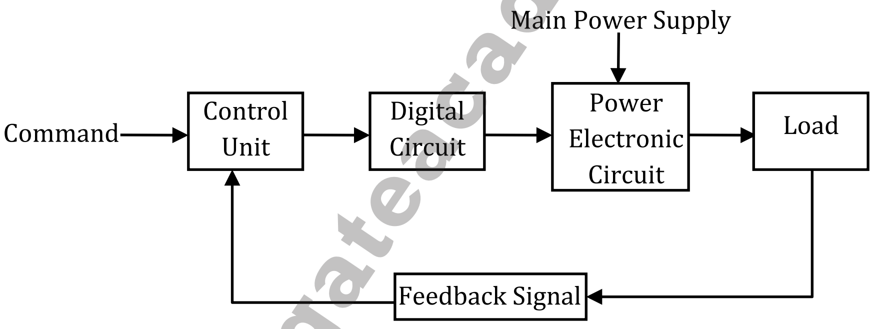
Applications of Power Electronics

In the modern era, power electronics has various applications and some of them are listed below;

- Commercial – Uninterruptible power supply (UPS)
- Aerospace – Aircraft power systems
- Industrial – Textile mills, cement mills, welding
- Telecommunication – Battery chargers
- Residential – Personal computers, vacuum cleaners
- Transportation – Street cars, trolley buses
- Utility Systems – HVDC, static circuit breakers

Basic Power Electronic Circuit Block Diagram

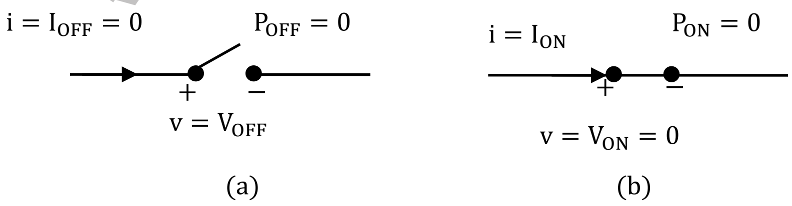
The figure below shows a basic power electronic system. The output of the power electronic circuit may be variable dc/variable ac voltage or it may be a variable voltage and variable frequency. The feedback component measures a parameter of the load like speed in case of a rotating machine. The difference between the target speed and measured speed controls the behaviour of power electronic circuit.



Block Diagram of a Typical Power Electronic System

Ideal Switches

There are several electronic devices, which serve as switches. We may first list out the desired features of ideal switches. The practical switches may then be studied with reference to these ideal characteristics. The features of ideal switches (with reference to the schematic shown in figure below) are

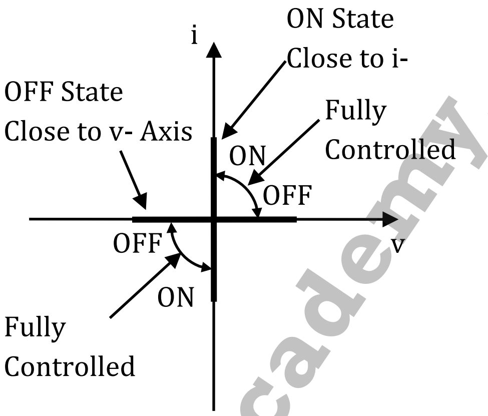


Ideal Switch

1. In the OFF state, the current passing through the switch is zero and the switch is capable of supporting any voltage across it. $I_{OFF} = 0; -\infty \le V_{OFF} \le +\infty$
2. In the ON state, the voltage across the switch is zero and the switch is capable of passing any current through it. $V_{ON} = 0; -\infty \le I_{ON} \le +\infty$
   The Power Dissipated in The Switch in the ON and OFF States is Zero

3. The switch can be turned ON and OFF instantaneously. $t_{on} = 0; t_{off} = 0$
4. The switch does not need energy to switch ON/OFF or OFF/ON or to be maintained in the ON/OFF states
5. The switch characteristics are stable under all ambient conditions

Features 1 and 2 leads to zero conduction and blocking losses. Feature 3 leads to zero switching losses. Feature 4 leads to zero control effort. Feature 5 makes the ideal switch indestructible. The operating points of the ideal switch on the V-I plane lie along the axis as shown in figure below. Practical devices, though not ideal, reach quite close to the characteristics of ideal switches.



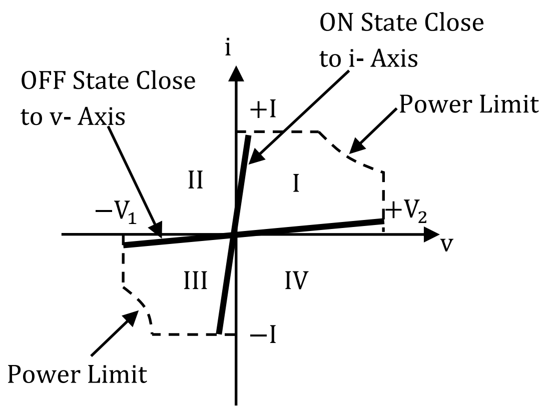
V-I Characteristics of the Ideal Switch

Practical Switches

Practical switches suffer from limitations on almost all the features of the ideal switches.

1. The OFF state current is nonzero. This current is referred to as the leakage current. The OFF state voltage blocking capacity is limited. $i = I_{OFF} \neq 0; -V \leq V_{OFF} \leq +V$
2. The ON state voltage is nonzero. This voltage is called the conduction voltage drop. The ON state current carrying capacity is limited. $V_{ON} \neq 0; -I \leq I_{ON} \leq I+$
   There is Finite Power Dissipation in the OFF State (Blocking Loss) and ON State (Conduction Loss)
3. Switching from one state to the other takes a finite time. Consequently the maximum operating frequency of the switch is limited. $t_{on} = 0; t_{off} = 0$
   The consequence of finite switching time is the associated switching losses.
   The switch transitions require external energy and so also the switch states.
   $E_{on} \neq 0; \quad E_{on/off} \neq 0$
   $E_{off} \neq 0; \quad E_{off/on} \neq 0$
   Practical Switches need Supporting Circuits (Drive Circuits) to Provide this Energy

The switch characteristics are thermally limited. The power dissipation in the device is nonzero. It appears as heat and raises the temperature of the device. To prevent unlimited rise in temperature of the device external aids are needed to carry away the generated heat from the device.
Practical switches suffer from a number of failure modes associated with the OFF state Voltage and ON state current limits.



Operational Boundaries of a Practical Switch

The operating points of practical switches on the v-i plane are shown in figure above. The steady state operating points lie close to the axis within certain limits. Further there is a safe operating area (SOA) on the v-i plane for transient operation.

Practical Power Switching Devices

There are several power switching devices available for use in PES. They may be classified as:

(A) Uncontrolled Switches

The state (ON/OFF) of the switch is determined by the state of the power circuit in which the device is connected. There is no control input to the device. Diodes are uncontrolled switches.

(B) Semi-controlled Switches

The switch may be turned to one of its states (OFF/ON) by suitable control input to its control terminal. The other state of the switch is reachable only through intervention from the power circuit. A thyristor is an example of this type of switch. It may be turned ON by a current injected into its gate terminal; but turning OFF a conducting thyristor is possible only by reducing the main current through the device to zero. **E.g.,** SCR

(C) Controlled Switches

Both the states of the switch (ON/OFF) are reachable through appropriate control signals applied to the control terminal of the device. Bipolar junction transistor (BJT), Field effect transistor (FET), Gate turn-off thyristor (GTO), Insulated gate bipolar transistor (IGBT) fall under this group of switches.

The Switches Desired in PES are Realized through a Combination of the above Devices

Losses in Practical Switch

The ideal switch is lossless. But practical switch is having

1. Conduction Loss
2. Blocking Loss
3. Switching Loss

Blocking Loss

The device passes low leakage current during OFF state and OFF state voltage is limited.

$I_{OFF} = I_{CES} \neq 0; 0 \leq V_{OFF} \leq V_{CES}$

$P_{Block} = I_{OFF} V_{OFF}$

Conduction Loss

The device offers small voltage drop across it when it conducts (ON)

$V_{ON} = V_{CE(sat)} \neq 0$ and carries a finite current.

$I \leq I_{ON} \leq I^+$

$0 < I_{ON} \leq I$

Switching Loss

(i) Switch takes a finite time to become ON (OFF to ON) – t_{on}

(ii) Switch takes a finite time to become OFF (ON to OFF) – t_{off}

The energy loss $(E_{on}) = \int V_{ON} I_{ON}\, dt$

$(E_{off}) = \int V_{OFF}\, I_{OFF}\, dt$

Classification of Power Diodes

Based on their operating characteristics, power semiconductor devices can be classified as below.

Uncontrolled Devices: Uncontrolled devices are the power semi-conductor devices whose V-I characteristics cannot be controlled. Their ON and OFF states are controlled by power supply. These are typically used in uncontrolled rectifiers.

E.g.: Power diodes

Controlled Devices: These devices can be switched ON/OFF by using a control signal.

E.g.: Power transistors

Semi-Controlled Devices: These devices can be partially controlled using a control signal.

E.g.: SCR can be turned ON using GATE signal, but cannot be turned OFF.

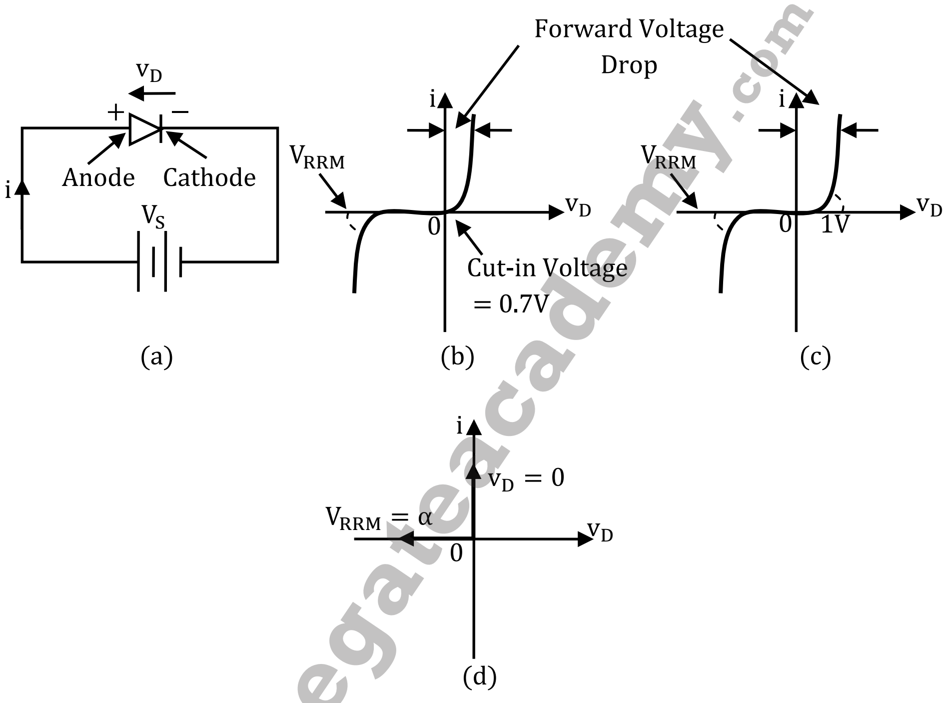
Also various power semiconductor devices are discussed in detail in subsequent sections.

Power Diodes: Power diodes belong to the class of uncontrolled power semiconductor devices. They are similar to low power p-n junction diodes called signal diodes. However to make them suitable for high power applications they are constructed with n^- layer between p^+ and n^+ layers to support large blocking voltage by controlling the width of depletion region. They can be used as freewheeling diodes in ac to dc conversion.

Peak Inverse Voltage (PIV): Peak inverse voltage is defined as largest reverse voltage that a diode can be subjected to PIV of diode is mainly helpful while designing any electronic circuit so as to ensure that worst case reverse voltage across diode is within allowable limits.

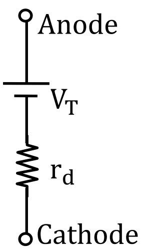
Transfer Characteristics of a Power Diode

When anode is positive with respect to cathode, diode is forward biased. When forward voltage across diode is slowly increased from 0 to cut-in voltage, diode current is almost zero. Above cut-in voltage, the diode current rises rapidly and the diode is said to conduct. When anode is negative with respect to cathode, diode is reverse biased. Figure below gives an idea about transfer characteristics of power diode. Here V_C is the cut-in voltage and V_{RM} is the PIV of diode D. For germanium diodes, V_C is 0.3V and for silicon diodes, V_C is 0.7V, but silicon diodes are popular as silicon is abundant in nature in the form of sand.



(a) A Forward-Baised Power Diode. i-v Characteristics of (b) Signal Diode (c) Power Diode and (d) Ideal Diode

Linear Model



Where, r_d – Dynamic Resistance; V_T – Terminal Voltage