Electrical Engineering

Power Electronics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

MADE EASY
Publications

MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

Power Electronics

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018

Contents

Power Electronics

■■■■

CHAPTER 1

Introduction

The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

1.1 Block Diagram of Power Electronic Systems

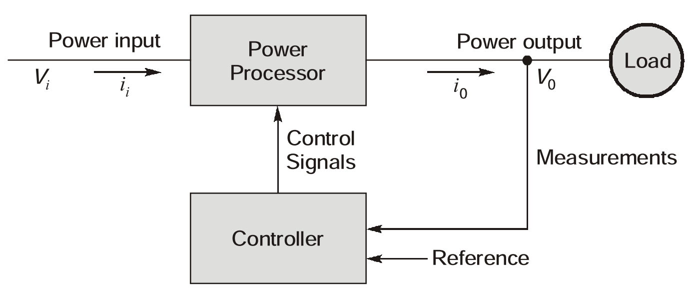


***Figure*-1.1**

Power electronics may be defined as the application of solid state electronics for the control and conversion of electric power.

History of Power Electronics

The history of power electronics began with the introduction of the mercury arc rectifier in 1900. The first electronics revolution began in 1948 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain and Schockley. The next break through, in 1956, was also from Bell Laboratories: the invention of the PNPN triggering transistor, which was defined as a thyristor or silicon controlled rectifier (SCR). The second electronics revolution began in 1958 with the development of the commercial thyristor by the General Electric Company. That was the beginning of a new era of power electronics. The micro electronics revolution gave us the ability to process a huge amount of information at incredible speed. The power electronics revolution is giving us the ability to shape and control large amounts of power with ever increasing efficiency.

Scope and Applications

1. Switch Mode (DC) Power Supplies and Uninterruptible Power Supplies

Advances in micro electronics fabrication technology have led to the development of computers, communication equipment and consumer electronics, all of which require regulated dc power supplies and often uninterruptible power supplies.

2. Energy Conservation

Increasing energy costs and the concern for the environment have combined to make energy conservation a priority. Adjustable speed motor drives, load proportional, capacity modulated heat pumps and air conditioners are examples of applying power electronics to achieve energy conservation.

3. Process Control and Factory Automation

There is a growing demand for the enhanced performance offered by adjustable speed driven pumps and compressors in process control. Robots in automated factories are powered by electric servo (adjustable speed and position) drives. It should be noted that the availability of process computers is a significant factor in making process control and factory automation feasible.

4. Transportation

In many countries, electric trains have been in widespread use for a long time. Now, there is also a possibility of using electric vehicles in large metropolitan areas to reduce smog and pollution. Electric vehicles would also require battery chargers that utilize power electronics.

5. Electro Technical Applications

These include equipment for welding, electroplating, and induction heating.

6. Utility Related Applications

One such application is in transmission of power over high voltage dc (HVDC) lines. Power electronics is also beginning to play a significant role as electric utilities attempt to utilize the existing transmission network to a higher capacity. Potentially, a large application is in the interconnection of photo voltaic and wind electric systems to the utility grid.

Power Electronic Applications

1. Residential

Refrigeration and freezers, Space heating, Air conditioning, Cooking, Lighting, Electronics (personal computers, other entertainment equipment).

2. Commercial

Heating, Ventilating, and Air conditioning, Central refrigeration, Lighting, Computers and Office equipment, Uninterruptible Power Supplies (UPSs), Elevators.

3. Industrial

Pumps, Compressors, Blowers and Fans, Machine tools (Robots), Arc furnaces, Induction furnaces, Lighting, Industrial lasers, Induction heating, Welding.

4. Transportation

Traction control of electric vehicles, Battery chargers for electric vehicles, Electric locomotives, Street cars, Trolley buses, Subways, Automotive electronics including engine controls.

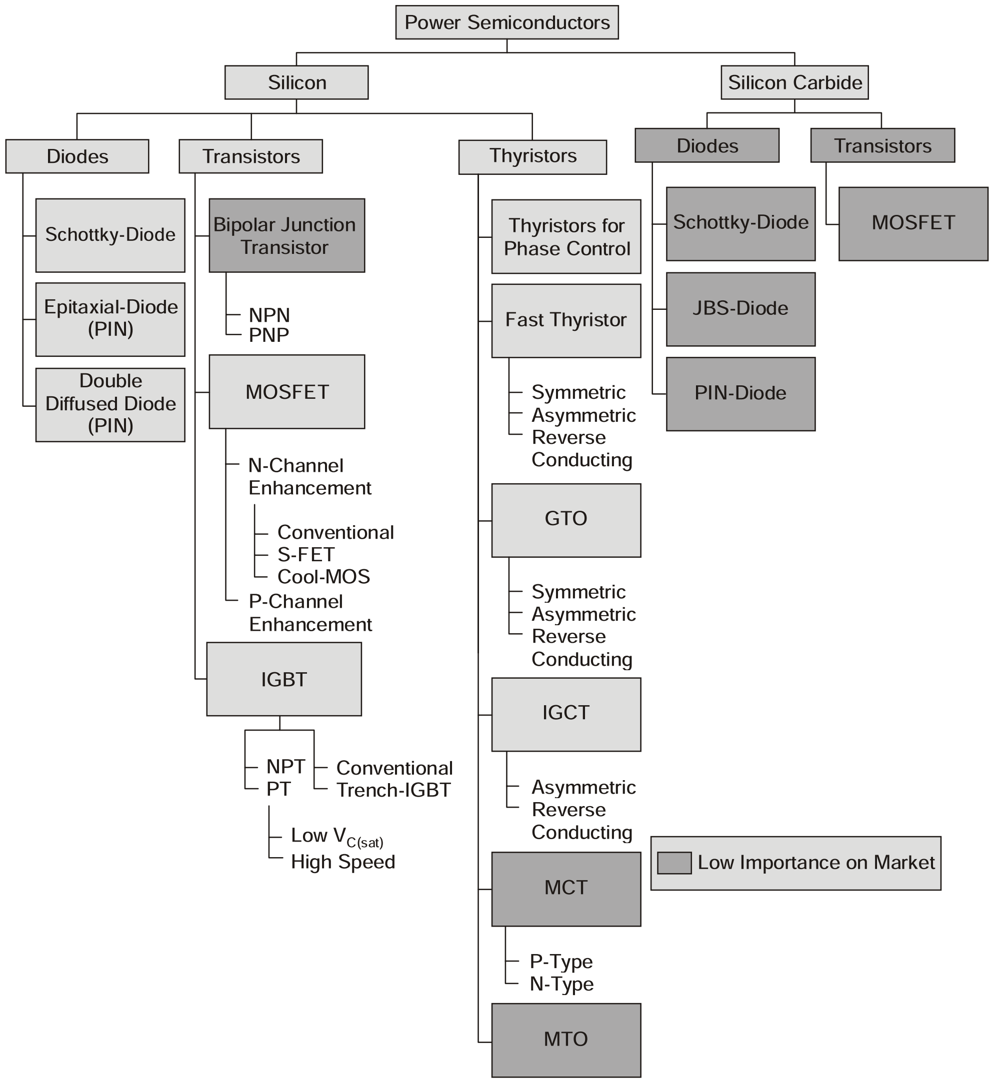


***Figure*-1.3 :** *Classification of the power semiconductors*

Characteristics and Specifications of Switches

There are many types of power switching devices. Each device, however, has its advantages and disadvantages and is suitable to specific applications. The motivation behind the development of any new device is to achieve the characteristics of a "***Super device***". The characteristics of any real device can be compared and evaluated with reference to the ideal characteristics of a super device.

Ideal Characteristics

The characteristics of an ideal switch are as follows:

- In the on-state when the switch is on, it must have (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; and (c) a low on-state resistance R_{ON}, tending to zero. Low R_{ON} causes low on-state power loss P_{ON}. These symbols are normally referred to under dc steady state conditions.

- In the off-state when the switch is off, it must have (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, and (c) a high off-state resistance R_{OFF}, tending to infinity. High R_{OFF} cause low off-state power loss P_{OFF}. These symbols are normally referred to under dc steady-state conditions.
- During the turn-on and turn-off process, it must be completely turned on and off instantaneously so that the device can be operated at high frequencies. Thus it must have (a) a low delay time t_d, tending to zero; (b) a low rise time t_r, tending to zero; (c) a low storage time t_s, tending to zero; and (d) a low fall time t_f, tending to zero.
- For turn-on and turn-off, it must require (a) a low gate-drive power P_G, tending to zero; (b) a low gate-drive voltage V_G, tending to zero; and (c) a low gate-drive current I_G, tending to zero.
- Both turn-on and turn-off must be controllable. Thus, it must turn-on with a gate signal (e.g., positive) and must turn-off with another gate signal (e.g., zero or negative).
- For turning on and off, it should require a pulse signal only, that is a small pulse with a very small width t_W, tending to zero.
- It must have a high *dv*/*dt*, tending to infinity. That is, the switch must be capable of handling rapid changes of the voltage across it.
- It must have a high *di*/*dt*, tending to infinity. That is, the switch must be capable of handling a rapid rise of the current through it.
- It requires very low thermal impedance from the internal junction to the ambient R_{JA}, tending to zero so that it can transmit heat to the ambient easily.
- The ability to sustain any fault current for a long time is needed; that is, it must have a high value of i^2t, tending to infinity.
- Negative temperature coefficient on the conducted current is required to result in an equal current sharing when the devices are operated in parallel.
- Low price is a very important consideration for reduced cost of the power electronics equipment.

Switch Specifications

There are many parameters that are important to the devices. The most important among these are:

- **Voltage ratings:** Forward and reverse repetitive peak voltages, and an on-state forward voltage drop.
- **Current ratings:** Average, root-mean-square (rms), repetitive peak, non-repetitive peak, and off-state leakage currents.
- **Switching speed or Frequency:** Transition from a fully non-conducting to a fully conducting state (turn-on) and from a fully conducting to a fully non-conducting state (turn-off) are very important parameters. The switching period T_S and frequency f_S are given by

$$f_S = \frac{1}{T_S} = \frac{1}{t_d + t_r + t_{on} + t_s + t_f + t_{off}}$$

  where t_{off} is the off time during which the switch remains off.
- ***di*/*dt* Rating:** The device needs a minimum amount of time before its whole conducting surface comes into play in carrying the full current. 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, known as a series snubber.

- ***dv/dt* Rating:** A semiconductor device has an internal junction capacitance C_J. If the voltage across the switch changes rapidly during turn-on, turn-off and also while connecting the main supply the initial current, the current $C_J\, dv/dt$ flowing through C_J may be too high, thereby causing damage to the device. The dv/dt of the voltage across the device is limited by connecting an *RC* circuit across the device, known as a shunt snubber, or simply snubber.
- **Switching losses:** During turn-on the forward current rises before the forward voltage falls, and during turn-off the forward voltage rises before the current falls. Simultaneous existence of high voltage and current in the device represents power losses. Because of their repetitiveness, they represent a significant part of the losses, and often exceed the on-state conduction losses.
- **Gate drive requirements:** The gate-drive voltage and current are important parameters to turn-on and turn-off a device. The gate-driver power and the energy requirement are very important parts of the losses and total equipment cost. With large and long current pulse requirements for turn-on and turn-off, the gate drive losses can be significant in relation to the total losses and the cost of the driver circuit can be higher than the device itself.
- **Safe Operating Area (SOA):** The amount of heat generated in the device is proportional to the power loss, that is the voltage current product. For this product to be constant $P = vi$ and equal to the maximum allowable value, the current must be inverse proportional to the voltage. This yields the SOA limit on the allowable steady-state operating points in the voltage current coordinates.
- **I^2t for fusing:** This parameter is needed for fuse selection. The $I^2\,t$ of the device must be less than that of the fuse so that the device is protected under fault current conditions.
- **Temperatures:** Maximum allowable junction, case and storage temperatures, usually between 150°C and 200°C for junction and case, and between –50°C and 175°C for storage.
- **Thermal resistance:** Junction to case thermal resistance, Q_{JC}, case to sink thermal resistance, Q_{CS}, and sink ambient thermal resistance, Q_{SA}. Power dissipation must be rapidly removed from the internal wafer through the package and ultimately to the cooling medium. The size of semiconductor power switches is small, not exceeding 150 mm, and the thermal capacity of a bare device is too low to safely remove the heat generated by internal losses. Power devices are generally mounted on heat sinks. Thus, removing heat represents a high cost of equipment.

Summary

With 'n' number of variables the maximum possible minterm or maxterm is equal to '2^n'.
As the technology for the power semiconductor devices and integrated circuits develops, the potential for the applications of power electronics becomes wider. The power converters fall generally into six categories:

- Rectifiers
- AC-DC converters
- AC-AC converters
- DC-DC converters
- DC-AC converters and
- Static switches

The design of power electronics circuits requires designing the power and control circuits. The voltage and current harmonics that are generated by the power converters can be reduced (or minimized) with a proper choice of the control strategy.

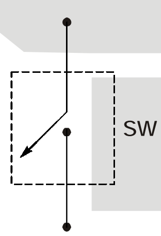
CHAPTER 7

Choppers

7.1 Definition

- A chopper is a static circuit that converts fixed dc input voltage to a variable dc output voltage directly. As choppers involve one stage conversion, these are more efficient.
- Chopper systems offer Smooth control, high efficiency, fast response and regeneration.
- The power semiconductor devices used for a chopper circuit can be
  (*i*) Force commutated Thyristor
  (*ii*) Power BJT
  (*iii*) Power MOSFET
  (*iv*) GTO (or)
  (*v*) IGBT

These devices, in general, can be represented by a switch SW with an arrow.



7.2 Principle of Operation of Step Down Chopper

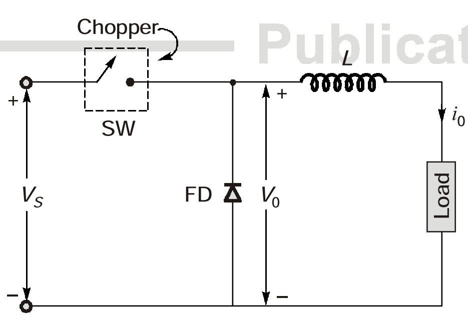


***Figure*-7.1**

During the period T_{on}, chopper is on and load voltage is equal to source voltage V_s. During the interval T_{off}, chopper is off, load current flows through the free wheeling diode FD. As a result, load terminals are short circuited by FD and load voltage is therefore zero during T_{off}.

During T_{on}, load current rises whereas during T_{off}, load current decays.

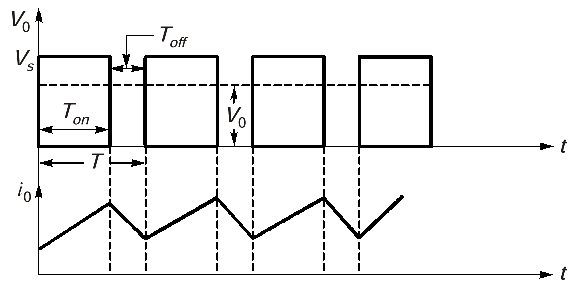


Figure-7.2

Average load voltage V_0 is given by

$$V_0 = \frac{T_{on}}{T_{on}+T_{off}} V_s = \frac{T_{on}}{T} V_s = \alpha\, V_s$$

$$\boxed{V_0 = \alpha\, V_s}$$

where, T_{on} = on-time; T_{off} = off-time

$$T = T_{on} + T_{off} = \text{chopping period}$$

$$\alpha = \frac{T_{on}}{T} = \text{duty cycle}$$

This load voltage can be controlled by varying duty cycle α.

$$\boxed{V_0 = f \cdot T_{on} \cdot V_s}$$

where, $f = \frac{1}{T}$ = chopping frequency

Variation of T_{on} means adjustment of pulse width, as such this scheme is also called Pulse-Width-Modulation scheme.

Average output current, $I_0 = \frac{V_0}{R} = \alpha \frac{V_s}{R}$

Rms value of output voltage $= \left[\frac{T_{on}}{T} \cdot V_s^2\right]^{1/2}$

$$\boxed{V_{0,\text{rms}} = \sqrt{\alpha} \cdot V_s}$$

(*i*) $I_0 = \frac{V_0}{R} = \frac{\alpha\, V_s}{R}$

$$\boxed{I_{s(avg)} = \frac{\alpha\, V_s}{R}}$$

(*ii*) $R_{in} = \frac{V_s}{I_s} = \frac{V_s}{\frac{\alpha\, V_s}{R}} = \frac{R}{\alpha}$

$$\boxed{R_{in} = \frac{R}{\alpha}}$$

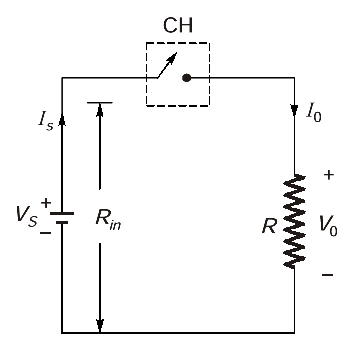


Figure-7.3

Example - 7.1 For the basic dc to dc step down converter, express the following variables as functions of V_s, R and duty cycle α in case load is resistive:

(a) Average output voltage and current
(b) Output current at the instant of commutation
(c) Average and rms freewheeling diode currents
(d) Rms value of the output voltage
(e) Rms and average thyristor currents
(f) Effective input resistance of the chopper.

Solution:

For a resistive load, output or load current waveform is similar to load voltage waveform.

(a) Average output voltage, $V_0 = \frac{T_{on}}{T}V_s = \alpha V_s$

Average output current, $I_0 = \frac{V_0}{R} = \frac{T_{on}}{T}.\frac{V_s}{R} = \alpha\frac{V_s}{R}$

(b) The output current is commutated by the thyristor at the instant $t = T_{on}$. Therefore, output current at the instant of commutation is $\frac{V_s}{R}$.

(c) For a resistive load, freewheeling diode *FD* does not come into play. Therefore, average and rms values of freewheeling diode currents are zero.

(d) RMS value of output voltage $= \left[\frac{T_{on}}{T}.V_s^2\right]^{1/2} = \sqrt{\alpha}.V_s$

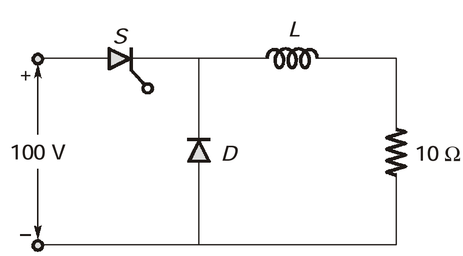
(e) Average thyristor current $= \frac{T_{on}}{T}.\frac{V_s}{R} = \alpha\frac{V_s}{R}$

Rms thyristor current $= \left[\frac{T_{on}}{T}.\left(\frac{V_s}{R}\right)^2\right]^{1/2} = \sqrt{\alpha}.\frac{V_s}{R}$

(f) Average source current = average thyristor current $= \alpha.\frac{V_s}{R}$

Effective input resistance of the chopper $= \frac{\text{dc source voltage}}{\text{average source current}} = \frac{V_s.R}{\alpha.V_s} = \frac{R}{\alpha}$

Example - 7.2 Figure shows a chopper operating from a 100 V dc input. The duty ratio of the main switch S is 0.8. The load is sufficiently inductive so that the load current is ripple free. The average current through the diode D under steady state is



(a) 1.6 A
(b) 6.4 A
(c) 8.0 A
(d) 10.0 A

CHAPTER 9

Resonant Converters

9.1 Introduction

The switching devices in converters with a pulse width modulation (PWM) control can be gated to synthesize the desired shape of output voltage or current. However, the devices are turned-on and off at the load current with a high di/dt value. The switches are subjected to a high voltage stress, and the switching power loss of a device increase linearly with the switching frequency. The turn-on and turn-off loss could be a significant portion of the total power loss. The electromagnetic interference is also produced due to high di/dt and dv/dt in the converter waveforms.

The disadvantages of PWM control can be eliminated or minimized if the switching devices are turned "on" and "off" when the voltage across a device or its current become zero. The voltage and current are forced to pass through zero crossing by creating an LC resonant circuit, thereby called a resonant pulse converter.

Series Resonant Inverters

The series resonant inverters are based on resonant current oscillation. The resonating components and switching device are placed in series with the load to form an underdamped circuit. The current through the switching devices falls to zero due to the natural characteristics of the circuit. If the switching element is a thyristor, it is said to be self-commutated. This type of inverter produces an approximately sinusoidal waveform at a high output frequency, ranging from 200 to 100 kHz, and is commonly used in relatively fixed output applications (e.g. induction heating, sonar transmitter, fluorescent lightening, or ultrasonic generators). Due to the high switching frequency, the size of resonating components is small.

Series-Resonant Inverters with Unidirectional Switches

The circuit diagram of a simple series inverter using two unidirectional thyristor of switches. When thyristor T_1 is fired, a resonant pulse of current flows through the load and the current falls to zero at $t = t_{1m}$ and T_1 is self commutated. Firing of thyristors T_2 causes a reverse resonant current through the load and T_2 is also self-commutated. The circuit operation can be divided into three modes and the equivalent circuits are shown in figure below. The gating signals for thyristors and the waveform for the load current and capacitor voltage are shown.

The series resonant circuit formed by L, C and load (assumed resistive) must be underdamped.

i.e., $$R^2 < \frac{4L}{C}$$

9.2 Zero-Current-Switching Resonant Converters

The switches of a zero-current-switching (ZCS) resonant converter turn on and off at zero current. The resonant circuit that consists of switch S_1, inductor L, and capacitor C is shown in figure. Inductor L is connected in series with a power switch S_1 to achieve ZCS. It is classified into two types: L type and M type. In both types, the inductor L limits the di/dt of the switch current, and L and C constitute a series-resonant circuit. When the switch current is zero, there is a current $i = C_j \frac{dv_T}{dt}$ flowing through the internal capacitance C_j due to a finite slope of the switch voltage at turn-off. This current flow causes power dissipation in the switch and limits the high switching frequency.

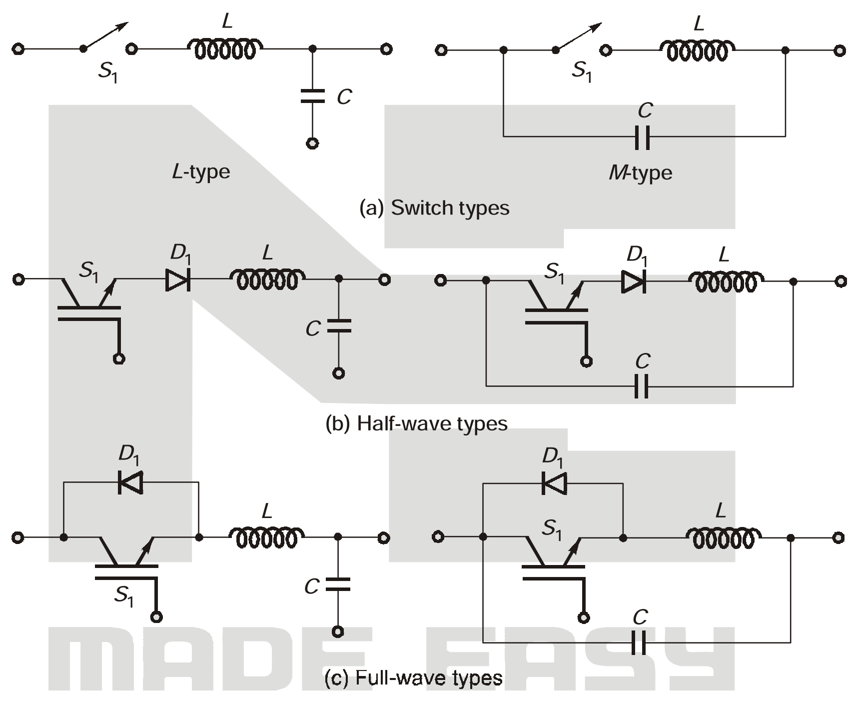


Figure : *Switch configuration for ZCS resonant converters*

9.3 L-Type ZCS Resonant Converter

An L-type ZCS resonant converter is shown in Fig. (a). The circuit operation can be divided into five modes, whose equivalent circuits are shown in Fig. (b). We shall redefine the time origin, $t = 0$, at the beginning of each mode.

Mode-1: This mode is valid for $0 \le t \le t_1$. Switch S_1 is turned on and diode D_m conducts. The inductor current i_L, which rises linearly, is given by

$$i_L = \frac{V_s}{L}t$$

This mode ends at time $t = t_1$ when $i_L\,(t = t_1) = I_0$. That is, $t_1 = \frac{I_0 L}{V_s}$.

CHAPTER 11

High Frequency Inductors and Transformers

11.1 Design of Magnetic Components for Power Electronics

Magnetic components, inductors and transformers, are an indispensible part of most power electronic converters. In this situation the power electronic equipment designer/user must be knowledgeable about the design and fabrication of these components in order to specify and use them properly in a given-application.

11.2 Magnetic Material and Cores

Magnetic Core Materials

Two broad classes of materials are used for magnetic cores for inductors and transformers. One class of materials are comprised of alloys principally of iron and small amounts of other elements including chrome and silicon. These alloys have large electrical conductivity compared with ferrities and large values of saturation flux density, near 1.8 tesla (T) (one T = 1 Wb/m^2). Two types of loss are found in iron alloy materials, hysteresis loss and eddy current loss. Iron alloys core materials (often termed magnetic steels) are usually used only in low-frequency (2 kHz or less for transformers) applications because of eddy current loss. Iron alloy magnetic materials must be laminated to reduce eddy current loss even at modest frequencies such as 60 Hz. Cores are also made from powdered iron and powdered iron alloys. Powdered iron cores consist of small (less than a skin depth in their largest dimension even at moderately high frequencies) iron particles electrically isolated from each other and thus have significantly greater resistivity than laminated cores. Thus powered iron cores have lower eddy current loss than laminated cores and can be used to higher frequencies.

The second broad class of materials used for cores are ferities. Ferrite materials are basically oxide mixtures of iron and other magnetic elements. They have quite large electrical resistivity but rather low saturation flux densities, typically about 0.3 T. Ferrites have only hysteresis loss. No significant eddy current loss occurs because of the high electrical resistivity. Ferrites are the material of choice for cores that operate at high frequencies (greater than 10 kHz) because of the low eddy current loss.

11.3 Hysteresis Loss

The hysteresis loss increases in all core materials increases with increases in ac flux density, B_{ac}, and operating or switching frequency, *f*. The general form of the loss per unit volume (sometimes termed the specific loss), $P_{m,\,sp,}$ is

$$P_{m,sp} = kf^a(B_{ac})^d$$

where *k*, *a*, and *d* are constants that vary from one material to another. This equation applies over a limited range of frequency and flux density with the range of validity being dependent on the specific material. The flux density B_{ac} in equation is the peak value of the ac waveform as shown in figure a if the flux density waveform has no time average. When the flux density waveform has a time-average B_{avg} as shown in Fig. b, then the appropriate value to use in equation is $B_{ac} = B - B_{avg}$. Core manufacturers provide detailed information about core loss usually in the form of graphs of specific loss $P_{m,\,sp}$ as a function of flux density B_{ac} with frequency as a parameter. An example of such a graph is shown in figure a for the ferrite material 3F3, and equation for this material is

$$P_{m,\,sp} = 1.5 \times 10^{-6} f^{1.3} (B_{ac})^{2.5}$$

with $P_{m,\,sp}$ in mW/cm^3 when *f* is in kHz and B_{ac} is in mT. In selected METGLAS alloys, the core losses may be comparable to ferrites, in spite of the fact that the amorphous alloys have much lower resistivity that ferrites and thus will have eddy current losses. For the METGLAS alloys 2705 M, the core losses are given by

$$P_{m,\,sp} = 3.2 \times 10^{-6} f^{1.8}(B_{ac})^2$$

The units in equation *b* are the same as in a. At a frequency of 100 kHz and a flux density B_{ac} of 100 mT, the 3F3 ferrite characterised by equation a would have $P_{m,\,sp} = 60$ mW/cm^3 while for the 2705 M alloy, $P_{m,\,sp} = 127$ mW/cm^3.

11.4 Skin Effect Limitations

When a magnetic core is made from conducting materials such as magnetic steels time-varying magnetic fields applied to the core will generate circulating current as is diagrammed in figure a. Using the right-hand rule, it can be seen that these currents, generically termed eddy currents, flow in directions such that secondary magnetic fields are produced that oppose the applied (primary) magnetic field. These opposing fields tend to screen the interior of the core from the applied field, and the total magnetic field in the core decays exponentially with distance into the core as is shown in figure b.

The characteristic decay length in the exponential is termed the skin depth and is given by

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

where $f = \omega/2\pi$ is the frequency (in hertz) of the applied magnetic field, μ is the magnetic permeability of the core material, and σ is the conductivity of the magnetic material If the cross-sectional dimensions of the core are large compared to the skin depth, then the interior of the core carries little or none of the applied magnetic flux as is diagrammed in figure b and the core is ineffective in its intended role of providing a low reluctance return path for the applied magnetic field. Typical values of the skin depth are quite small even at low frequencies (typically 1 mm at 60 Hz) because of the large permeability of the materials and the skin depth becomes more of a problem as the applied frequency increases.