A

Project Report

on

# "Development Of High Voltage Pulse Generator Module"

Submitted in partial fulfillment of the requirements

of the degree of

Bachelor of Engineering in Electrical Engineering

Submitted by

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# DECLARATION

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declared that I have adhered to all principles of academic honesty and integrity and have not represented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission have not been taken when needed.

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# ACKNOWLEDGEMENT

It gives me immense pleasure to present this project on “**Development Of High Voltage Pulse Generator Module**” carried out at AIKTC , New Panvel in accordance with prescribed syllabus of University of Mumbai for Electrical Engineering. I express my heartfelt gratitude to those who directly and indirectly contributed towards the completion of this project. I would like to thanks Mr. Abdul Razak Honnutagi , Principal, ACEM for allowing me to undertake this guide Prof. YAKUB KHAN for continuous support. I would like to thanks all the faculty members, non-teaching staffs of Electrical Engineering of our College for their direct and indirect support and suggestion for performing the project.

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# ABSTRACT

The main objective of this project is to develop a circuit to generate a high-voltage pulse with less rise time .In this project we are use two topology in the first topology DC from the low-voltage DC by pulse generator principle. It develops an output approximately twentysix times to that of the input voltage by using capacitor and SCR combination. If the input voltage applied is around 600v volts DC, then the output voltage is around 15.6 Kvolts DC in this we get the rise time less than 300 nsec

In second topology we generate high voltage pulse by giving high voltage DC at the input but In this we get the rise time less than 10 nsec . In this the input is 10 KV and the output is 9.6 KV with rise time less than 10 nsec. In this we are using RLC circuit .

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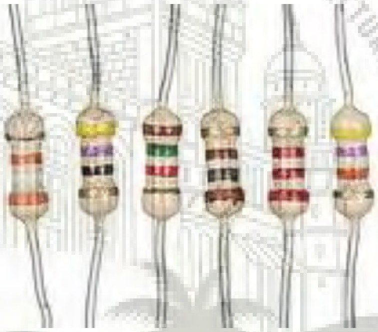
# CHAPTER 1 : INTRODUCTION

Today the range of high-voltage applications is no longerconfined to the high power industry. Several applications,such as X-rays for medical use, gas lasers for plasma technology, food sterilization, air pollution control, and plasmatreatment surface techniques, need high-voltage (several kilo-volts) fast rising pulses. This requires efficient and flexiblepulsed power circuits with optimization of all components.In spite of the new developments in solid-state-based pulsedpower circuits, achieved with the technological growth inpower electronics topologies and semiconductor characteristics improvements, the transformer is still a crucial part in mostof these high-voltage circuits. High voltage is often obtained from a pulse-generating circuit driving a high-voltage pulse transformer, which increases the output pulse voltage to the value needed at the load, reducing the voltage stress in the pulse generating circuit components, especially on the semiconductors.However, the design of the pulse transformer is one of themost critical tasks, due to the characteristics of high-voltage transformers (winding turns ratio usually greater than 1:10,large insulation gap between windings and between windinglayers), which increase the values of the parasitic elements,inter-winding capacitances, and equivalent leakage inductance,normally associated, respectively, with the electrostatic energy stored between windings and with the magnetic energy storedoutside the core. These elements, related with the non ideal behavior of the transformer, extend the pulse rise time andcause overshoot and oscillations.To overcome problems caused by the parasitic elements, newtransformer design methods and resonant topologies, have been used. Even though, all of these techniques must coexist with the fact that the transformer must sustain the total voltage between the primary and secondary windings,which is sometimes fairly expensive to accomplish.The most attractive, easy to assemble, and least expensive winding configuration for high-voltage is the core-type trans-former, with the primary and secondary wound on different core legs, as keeping the necessary insulation distance. This primary and secondary windings configuration is normally presented in high-leakage transformers.However, the magnetic coupling between primary and secondary windings is relatively weak and the equivalent leakage inductance opposes significantly to the rise of the output voltage pulse.Considering the leakage inductance proportional to the mag-netic energy stored outside the core, the pulse rise time can be reduced, decreasing this energy. A way to modify the distribution of the magnetic energy outside the core is to use auxiliary windings.Two suitable windings, fitted with a certain number of turns, can produce a magnetic flux that attempts to compensate the primary and secondary leakage fluxes, decreasing the total equivalent leakage inductance in the transformer and thus reducing the pulse rise time.in this project we are generate high voltage pulse with rise time less than 350 nsec with the help of pulse transformer and SCR switch.

# CHAPTER 2: RESISTOR , INDUCTOR AND CAPACITOR

## 2.1.1 Resistor

A **resistor** is a passive two-terminal electrical component that implements electrical resistance as a circuit element In electronic circuits, resistors are used to reduce current flow, adjust signal levels, to divide voltages, bias active elements, and terminate transmission lines, among other uses. High-power resistors that can dissipate many watts of electrical power as heat, may be used as part of motor controls, in power distribution systems, or as test loads for generators. Fixed resistors have resistances that only change slightly with temperature, time or operating voltage. Variable resistors can be used to adjust circuit elements (such as a volume control or a lamp dimmer), or as sensing devices for heat, light, humidity, force, or chemical activity.



## 2.1.2 Electronic symbols and notation

Two typical schematic diagram symbols are as follows:

(a) resistor, IEC resistor symbol

(b) rheostat(variable resistor)

(c) potentiometer

## 2.1.3 Conductors and resistors

Substances in which electricity can flow are called conductors. A piece of conducting material of a particular resistance meant for use in a circuit is called a resistor. Conductors are made of high-conductivity materials such as metals, in particular copper and aluminium. Resistors, on the other hand, are made of a wide variety of materials depending on factors such as the desired resistance, amount of energy that it needs to dissipate, precision, and costs.

## 2.1.4 Theory of operation

### 2.1.4.1 Ohm's law

For many materials, the current *I* through the material is proportional to the voltage *V* applied across it:

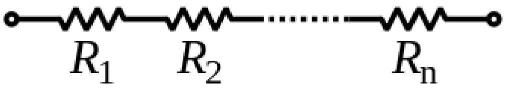
$$I \propto V$$

over a wide range of voltages and currents. Therefore, the resistance and conductance of objects or electronic components made of these materials is constant. This relationship is called Ohm's law, and materials which obey it are called ***ohmic*** materials. Examples of ohmic components are wires and resistors. The current-voltage (IV) graph of an ohmic device consists of a straight line through the origin with positive slope.

Other components and materials used in electronics do not obey Ohm's law; the current is not proportional to the voltage, so the resistance varies with the voltage and current through them. These are called *nonlinear* or ***non ohmic***. Examples include diodes and fluorescent lamps. The IV curve of a **non ohmic** device is a curved line.

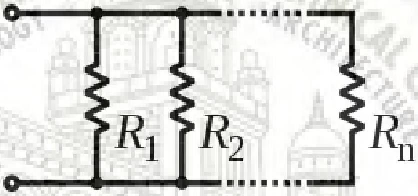
### 2.1.4.2 Series and parallel resistors

The total resistance of resistors connected in series is the sum of their individual resistance values.



**$R = R_1 + R_2 + \ldots + R_n$**

The total resistance of resistors connected in parallel is the reciprocal of the sum of the reciprocals of the individual resistors.



**$1 / R = 1 / R_1 + 1 / R_2 + \ldots + 1 / R_n$**

## 2.1.5 Dependence of resistance on other conditions

### 2.1.5.1 Temperature dependence

Near room temperature, the resistivity of metals typically increases as temperature is increased, while the resistivity of semiconductors typically decreases as temperature is increased. The resistivity of insulators and electrolytes may increase or decrease depending on the system.

As a consequence, the resistance of wires, resistors, and other components often change with temperature. This effect may be undesired, causing an electronic circuit to malfunction at extreme temperatures. In some cases, however, the effect is put to good use. When temperature-dependent resistance of a component is used purposefully, the component is called a resistance thermometer or thermistor. (A resistance thermometer is made of metal, usually platinum, while a thermistor is made of ceramic or polymer.)

Resistance thermometers and thermistors are generally used in two ways. First, they can be used as thermometers: By measuring the resistance, the temperature of the environment can be inferred. Second, they can be used in conjunction with Joule heating (also called self-heating): If a large current is running through the resistor, the resistor's temperature rises and therefore its resistance changes. Therefore, these components can be used in a circuit-protection role similar to fuses, or for feedback in circuits, or for many other purposes. In general, self-heating can turn a resistor into a nonlinear and hysteretic circuit element.

If the temperature *T* does not vary too much, a linear approximation is typically used:

$$R(T) = R_0 + [\ 1 + \propto (T - T_0)]$$

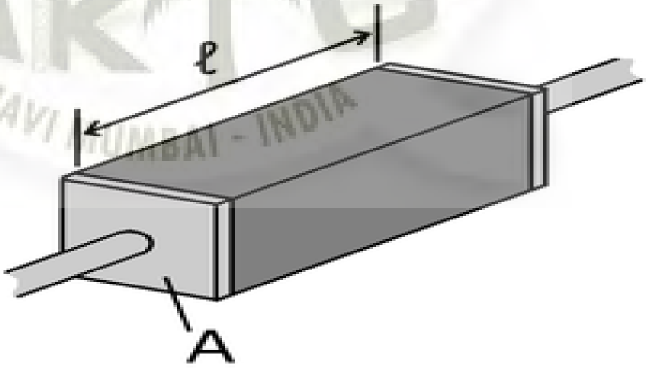
Where $\propto$ is called the *temperature coefficient of resistance*, $T_0$ is a fixed reference temperature (usually room temperature), and $R_0$ is the resistance at temperature.

## 2.1.6 Relation to resistivity and conductivity

The resistance of a given object depends primarily on two factors: What material it is made of, and its shape. For a given material, the resistance is inversely proportional to the cross-sectional area; for example, a thick copper wire has lower resistance than an otherwise-identical thin copper wire. Also, for a given material, the resistance is proportional to the length; for example, a long copper wire has higher resistance than an otherwise-identical short copper wire. The resistance R and conductance G of a conductor of uniform cross section, therefore, can be computed as

$$R = \rho\ l/A$$

$$G = \sigma\ A/l$$



where l is the length of the conductor, measured in metres [m], *A* is the cross-sectional area of the conductor measured in square metres [m²], σ (sigma) is the electrical conductivity measured in siemens per meter ($S{\cdot}m^{-1}$), and ρ (rho) is the electrical resistivity (also called *specific electrical resistance*) of the material, measured in ohm-metres (Ω·m). The resistivity and conductivity are proportionality constants, and therefore depend only on the material the wire is made of, not the geometry of the wire. Resistivity and conductivity are reciprocals: **$\rho = 1/\sigma$** . Resistivity is a measure of the material's ability to oppose electric current.

Another situation for which this formula is not exact is with alternating current (AC), because the skin effect inhibits current flow near the center of the conductor. For this reason, the *geometrical* cross-section is different from the *effective* cross-section in which current actually flows, so resistance is higher than expected. Similarly, if two conductors near each other carry AC current, their resistances increase due to the proximity effect. At commercial power frequency, these effects are significant for large conductors carrying large currents, such as busbars in an electrical substation, or large power cables carrying more than a few hundred amperes.

The resistivity of different materials varies by an enormous amount: For example, the conductivity of teflon is about $10^{30}$ times lower than the conductivity of copper. Why is there such a difference? Loosely speaking, a metal has large numbers of "delocalized" electrons that are not stuck in any one place, but free to move across large distances, whereas in an insulator (like teflon), each electron is tightly bound to a single molecule, and a great force is required to pull it away. Semiconductors lie between these two extremes.

## 2.1.7 Non ideal properties

Practical resistors have a series inductance and a small parallel capacitance; these specifications can be important in high-frequency applications. In a low-noise amplifier or pre-amp, the noise characteristics of a resistor may be an issue. The temperature coefficient of the resistance may also be of concern in some precision applications.

The unwanted inductance, excess noise, and temperature coefficient are mainly dependent on the technology used in manufacturing the resistor. They are not normally

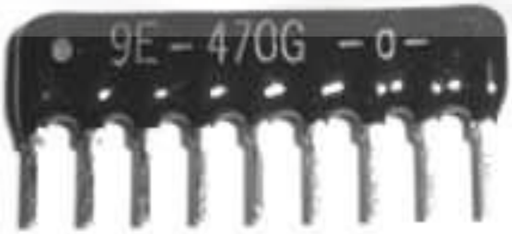
specified individually for a particular family of resistors manufactured using a particular technology. A family of discrete resistors is also characterized according to its form factor, that is, the size of the device and the position of its leads (or terminals) which is relevant in the practical manufacturing of circuits using them.Practical resistors are also specified as having a maximum power rating which must exceed the anticipated power dissipation of that resistor in a particular circuit: this is mainly of concern in power electronics applications. Resistors with higher power ratings are physically larger and may require heat sinks. In a high-voltage circuit, attention must sometimes be paid to the rated maximum working voltage of the resistor. While there is no minimum working voltage for a given resistor, failure to account for a resistor's maximum rating may cause the resistor to incinerate when current is run through it.

## 2.1.8 Measurement

The value of a resistor can be measured with an ohmmeter, which may be one function of a multimeter. Usually, probes on the ends of test leads connect to the resistor. A simple ohmmeter may apply a voltage from a battery across the unknown resistor (with an internal resistor of a known value in series) producing a current which drives a meter movement. The current, in accordance with Ohm's law, is inversely proportional to the sum of the internal resistance and the resistor being tested, resulting in an analog meter scale which is very non-linear, calibrated from infinity to 0 ohms. A digital multimeter, using active electronics, may instead pass a specified current through the test resistance. The voltage generated across the test resistance in that case is linearly proportional to its resistance, which is measured and displayed. In either case the low-resistance ranges of the meter pass much more current through the test leads than do high-resistance ranges, in order for the voltages present to be at reasonable levels (generally below 10 volts) but still measurable.

## 2.1.9 Fixed resistor

### 2.1.9.1 Lead arrangements



Through-hole components typically have "leads" (pronounced /liːdz/) leaving the body "axially," that is, on a line parallel with the part's longest axis. Others have leads coming off their body "radially" instead. Other components may be SMT(surface mount technology), while high power resistors may have one of their leads designed into the heat sink.

### 2.1.9.2 Carbon composition

Carbon composition resistors (CCR) consist of a solid cylindrical resistive element with embedded wire leads or metal end caps to which the lead wires are attached. The body of the resistor is protected with paint or plastic. Early 20th-century carbon composition resistors had uninsulated bodies; the lead wires were wrapped around the ends of the resistance element rod and soldered. The completed resistor was painted for color-coding of its value.

The resistive element is made from a mixture of finely powdered carbon and an insulating material, usually ceramic. A resin holds the mixture together. The resistance is determined by the ratio of the fill material (the powdered ceramic) to the carbon. Higher concentrations of carbon, which is a good conductor, result in lower resistance. Carbon composition resistors were commonly used in the 1960s and earlier, but are not popular for general use now as other types have better specifications, such as tolerance, voltage dependence, and stress. Carbon composition resistors change value when stressed with over-voltages.

## 2.1.10 Variable resistors

### 2.1.10.1 Adjustable resistors

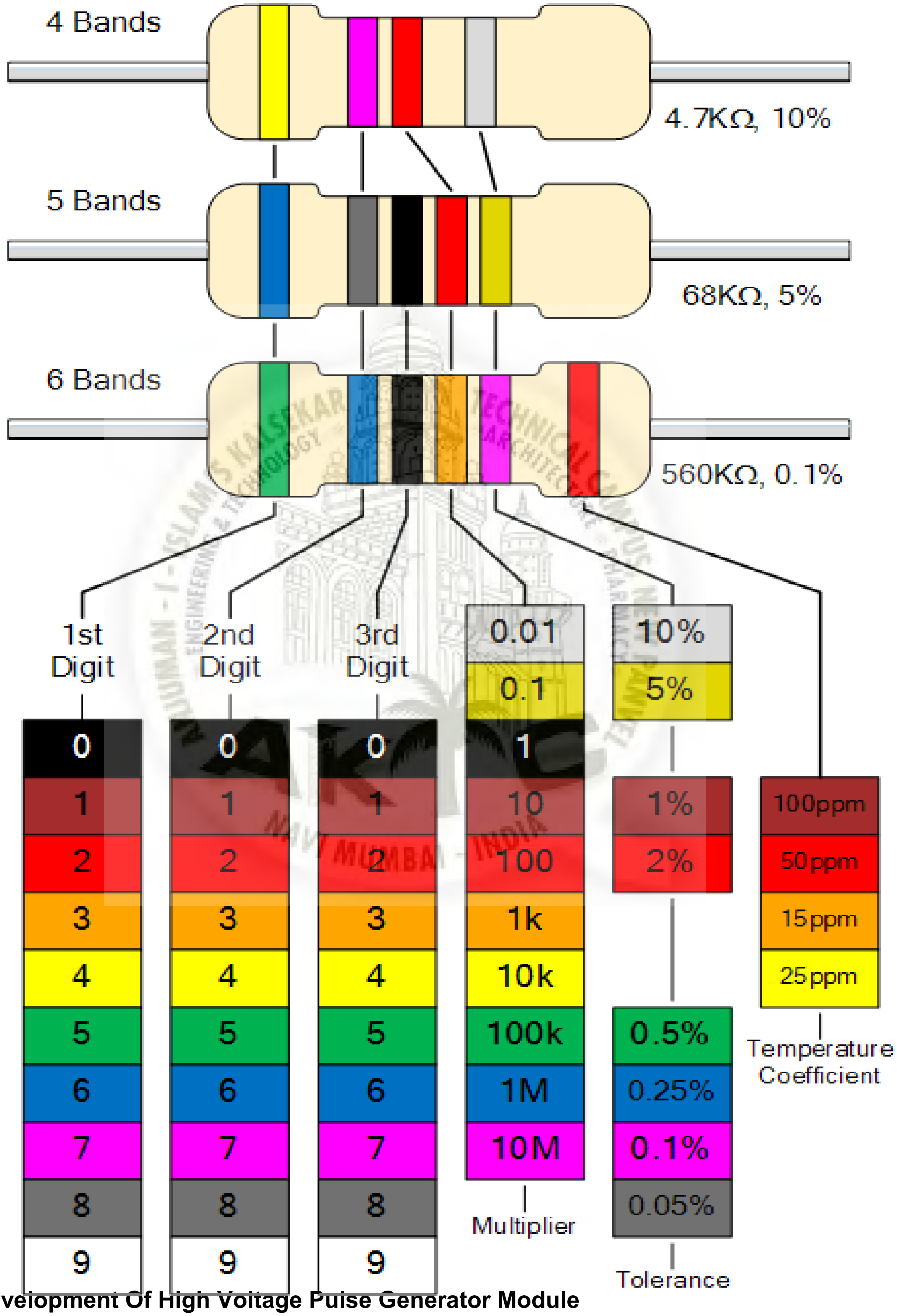
A resistor may have one or more fixed tapping points so that the resistance can be changed by moving the connecting wires to different terminals. Some wirewound power resistors have a tapping point that can slide along the resistance element, allowing a larger or smaller part of the resistance to be used.

Where continuous adjustment of the resistance value during operation of equipment is required, the sliding resistance tap can be connected to a knob accessible to an operator. Such a device is called a rheostat and has two terminals.

## 2.1.10.2 Potentiometers

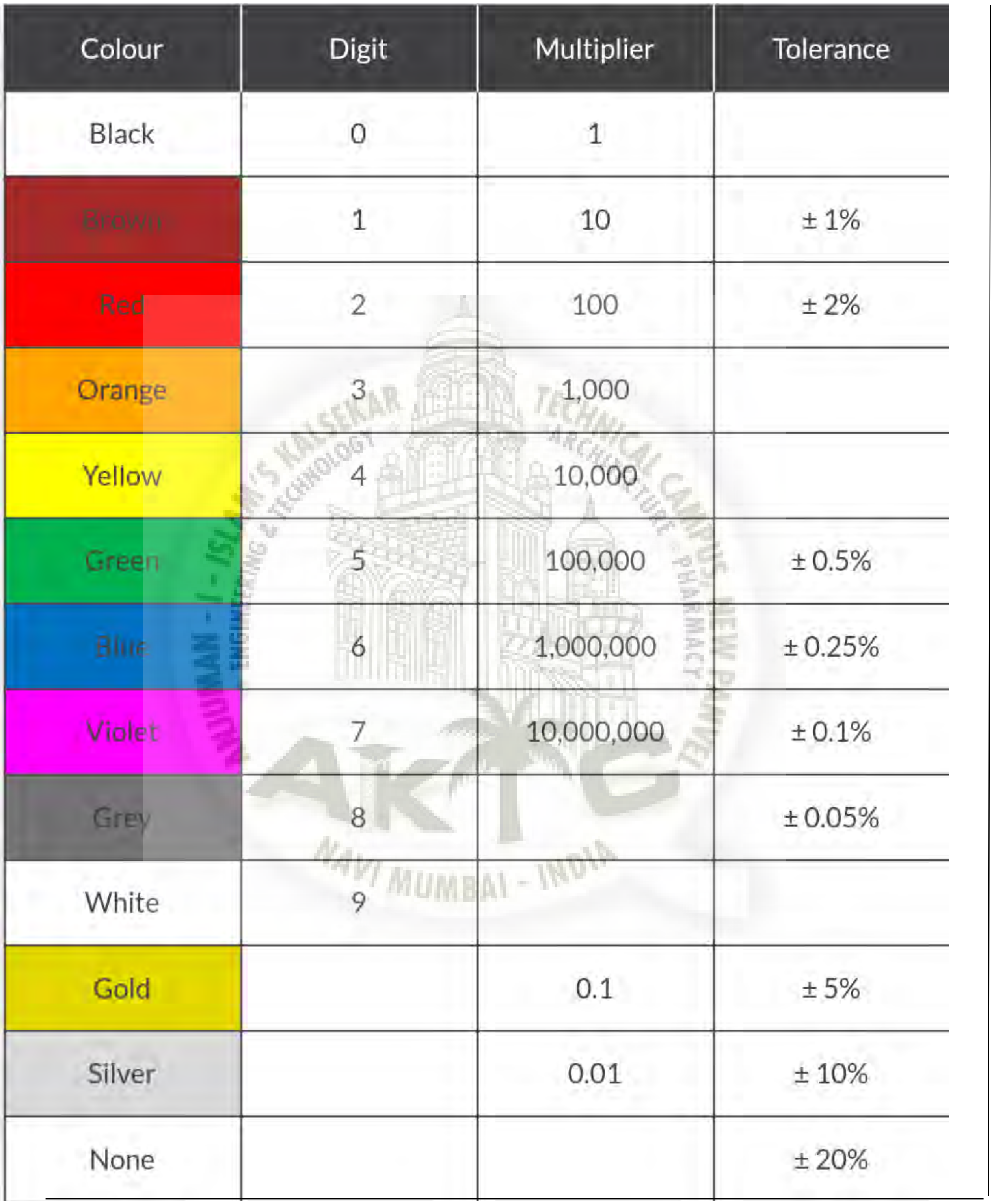
A potentiometer (colloquially, *pot*) is a three-terminal resistor with a continuously adjustable tapping point controlled by rotation of a shaft or knob or by a linear slider. The name *potentiometer* comes from its function as an adjustable voltage divider to provide a variable potential at the terminal connected to the tapping point. Volume control in an audio device is a common application of a potentiometer. A typical low power potentiometer *(see drawing)* is constructed of a flat resistance element *(B)* of carbon composition, metal film, or conductive plastic, with a springy phosphor bronze wiper contact *(C)* which moves along the surface. An alternate construction is resistance wire wound on a form, with the wiper sliding axially along the coil. These have lower resolution, since as the wiper moves the resistance changes in steps equal to the resistance of a single turn.

## 2.1.11 The Standard Resistor Colour Code Chart



| 1st Digit | 2nd Digit | 3rd Digit | Multiplier | Tolerance | Temperature Coefficient |
|---|---|---|---|---|---|
| | | | 0.01 | 10% | |
| | | | 0.1 | 5% | |
| 0 | 0 | 0 | 1 | | |
| 1 | 1 | 1 | 10 | 1% | 100ppm |
| 2 | 2 | 2 | 100 | 2% | 50ppm |
| 3 | 3 | 3 | 1k | | 15ppm |
| 4 | 4 | 4 | 10k | | 25ppm |
| 5 | 5 | 5 | 100k | 0.5% | |
| 6 | 6 | 6 | 1M | 0.25% | |
| 7 | 7 | 7 | 10M | 0.1% | |
| 8 | 8 | 8 | | 0.05% | |
| 9 | 9 | 9 | | | |

## 2.1.11.1 The Resistor Colour Code Table



| Colour | Digit | Multiplier | Tolerance |
|---|---|---|---|
| Black | 0 | 1 | |
| Brown | 1 | 10 | ± 1% |
| Red | 2 | 100 | ± 2% |
| Orange | 3 | 1,000 | |
| Yellow | 4 | 10,000 | |
| Green | 5 | 100,000 | ± 0.5% |
| Blue | 6 | 1,000,000 | ± 0.25% |
| Violet | 7 | 10,000,000 | ± 0.1% |
| Grey | 8 | | ± 0.05% |
| White | 9 | | |
| Gold | | 0.1 | ± 5% |
| Silver | | 0.01 | ± 10% |
| None | | | ± 20% |

# 2.2 Inductor

For inductors whose magnetic properties rather than electrical properties matter, see electromagnet.

An inductor, also called a coil, choke, or reactor, is a passive two-terminal electrical component that stores energy in a magnetic field when electric current flows through it. An inductor typically consists of an insulated wire wound into a coil around a core.

When the current flowing through an inductor changes, the time-varying magnetic field induces an electromotive force (e.m.f.) (voltage) in the conductor, described by Faraday's law of induction. According to Lenz's law, the induced voltage has a polarity (direction) which opposes the change in current that created it. As a result, inductors oppose any changes in current through them.

An inductor is characterized by its inductance, which is the ratio of the voltage to the rate of change of current. In the International System of Units (SI), the unit of inductance is the henry (H) named for 19th century American scientist Joseph Henry. In the measurement of magnetic circuits, it is equivalent to weber/ampere. Inductors have values that typically range from 1 µH ($10^{-6}$ H) to 20 H. Many inductors have a magnetic core made of iron or ferriteinside the coil, which serves to increase the magnetic field and thus the inductance. Along with capacitors and resistors, inductors are one of the three passive linear circuit elements that make up electronic circuits. Inductors are widely used in alternating current (AC) electronic equipment, particularly in radio equipment. They are used to block AC while allowing DC to pass; inductors designed for this purpose are called chokes. They are also used in electronic filters to separate signals of different frequencies, and in combination with capacitors to make tuned circuits, used to tune radio and TV receivers.

## 2.2.1 Description

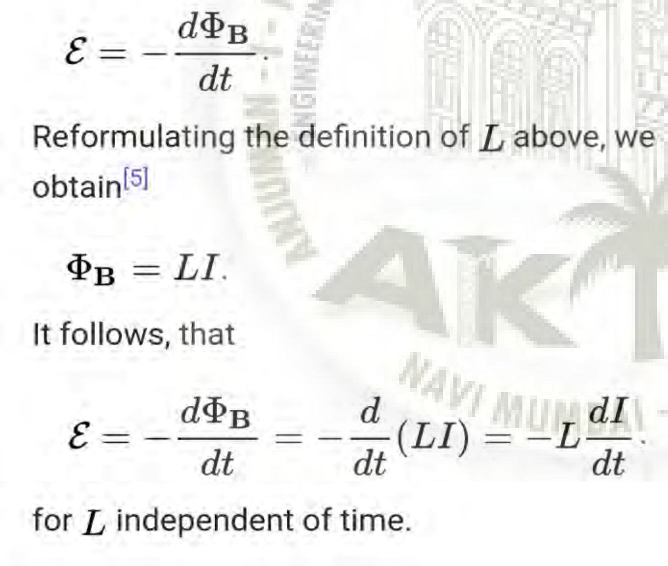
An electric current flowing through a conductor generates a magnetic field surrounding it. The magnetic flux linkage **$\phi_B$** generated by a given current **I** depends on the geometric shape of the circuit. Their ratio defines the inductance **L**. Thus

$$L = \phi_B / I$$

The inductance of a circuit depends on the geometry of the current path as well as the magnetic permeability of nearby materials. An inductor is a component consisting of a wire or other conductor shaped to increase the magnetic flux through the circuit, usually in the shape of a coil or helix. Winding the wire into a coil increases the number of times the magnetic flux lines link the circuit, increasing the field and thus the inductance. The more turns, the higher the inductance. The inductance also depends on the shape of the coil, separation of the turns, and many other factors. By adding a "magnetic core" made of a ferromagnetic material like iron inside the coil, the magnetizing field from the coil will induce magnetization in the material, increasing the magnetic flux. The high permeability of a ferromagnetic core can increase the inductance of a coil by a factor of several thousand over what it would be without it.

## 2.2.2 Constitutive equation

Any change in the current through an inductor creates a changing flux, inducing a voltage across the inductor. By Faraday's law of induction, the voltage induced by any change in magnetic flux through the circuit is given by



$$\mathcal{E} = -\frac{d\Phi_{\mathbf{B}}}{dt}.$$

Reformulating the definition of $L$ above, we obtain[5]

$$\Phi_{\mathbf{B}} = LI.$$

It follows, that

$$\mathcal{E} = -\frac{d\Phi_{\mathbf{B}}}{dt} = -\frac{d}{dt}(LI) = -L\frac{dI}{dt}.$$

for $L$ independent of time.

So inductance is also a measure of the amount of electromotive force (voltage) generated for a given rate of change of current. For example, an inductor with an inductance of 1 henry produces an EMF of 1 volt when the current through the inductor changes at the rate of 1 ampere per second. This is usually taken to be the constitutive relation (defining equation) of the inductor.

The dual of the inductor is the capacitor, which stores energy in an electric field rather than a magnetic field. Its current–voltage relation is obtained by exchanging current and voltage in the inductor equations and replacing L with the capacitance C.

## 2.2.3 Lenz's law

The polarity (direction) of the induced voltage is given by Lenz's law, which states that the induced voltage will be such as to oppose the change in current. For example, if the current through an inductor is increasing, the induced voltage will be positive at the terminal through which the current enters and negative at the terminal through which it leaves, tending to oppose the additional current. The energy from the external circuit necessary to overcome this potential "hill" is being stored in the magnetic field of the inductor. If the current is decreasing, the induced voltage will be negative at the terminal through which the current enters and positive at the terminal through which it leaves, tending to maintain the current. In this case energy from the magnetic field is being returned to the circuit.

## 2.2.4 Energy stored in an inductor

One intuitive explanation as to why a potential difference is induced on a change of current in an inductor goes as follows:

When there is a change in current, there is a change in the strength of the induced magnetic field. Without loss of generality, let us assume we have increased the current over our inductor, and now our induced magnetic field is stronger. This, however, does not come without a price. Magnetic fields store energy, and the stronger they are the more energy they store. To make up for an *increase in magnetic potential energy* in the induced magnetic field, we must *take some energy* from the inductor *in the form of electrical energy*. Here we experience a drop in *electric* potential over the inductor i.e. a negative voltage. Once we stop increasing the current, and keep it constant, no additional energy must be supplied to the magnetic field and the electrical potential returns to its original value, thus we see no voltage drop over the inductor.

Likewise, when the current decreases, the induced magnetic field strength decreases, and that superfluous energy must be returned. Hence, we experience an increase in *electrical* potential over the inductor.

## 2.2.5 Derivation

We know that the work done per unit charge on a charged particle when passing the inductor is **-ε**. The negative sign indicates that the work is done *against* the emf, and is not done *by* the emf.

By knowing that **I** is the charge per unit time, it follows that the rate of energy **W** done against the emf is given by

$$\frac{dW}{dt} = -\mathcal{E}I = L\frac{dI}{dt} \cdot I = LI \cdot \frac{dI}{dt}.$$

We may proceed to state that

$$dW = LI \cdot dI.$$

If the magnetic field in the inductor approaches the level at which the core saturates, the inductance will begin to change with current and thus we will henceforth denote the inductance **L** with **$L_1$** to accommodate for this dependency. Neglecting losses, the energy **W** stored by an inductor with a current **$I_0$** passing through it is equal to the amount of work required to establish the current through the inductor. This is given by:

$$W = \int_0^{I_0} L_I I dI.$$

If the inductance is constant over the current range $L := L_I$ , the stored energy is

$$W = L\int_0^{I_0} IdI$$

$$W = \frac{1}{2}LI_0^2$$

For inductors with magnetic cores, the above equation is only valid for linear regions of the magnetic flux, at currents below the saturation level of the inductor, where the inductance is approximately constant. Where this is not the case, the integral form must be used with **$L_1$** variable

## 2.2.6 Ideal and real inductors

In circuit theory, inductors are idealized as obeying the mathematical relation (2) above precisely. An "ideal inductor" has inductance, but no resistance or capacitance, and does not dissipate energy. However real inductors have nonideal properties which cause their behavior to depart from this simple model. They have resistance (due to the resistance of the wire and energy losses in the core), and parasitic capacitance due to electric potential between the turns of wire. This capacitive reactance rises with frequency; at some frequency, the inductor will behave as a resonant circuit, becoming self-resonant. Above the self-resonant frequency the capacitive reactance is the dominant part of the impedance. At higher frequencies, resistive losses in the windings increase due to skin effect and proximity effect.

Inductors with ferromagnetic cores have additional energy losses due to hysteresis and eddy currents in the core, which increase with frequency. At high currents, magnetic core inductors also show sudden departure from ideal behavior due to nonlinearity caused by magnetic saturation of the core. An inductor radiates electromagnetic energy into surrounding space and circuits, and may absorb electromagnetic emissions from other circuits, causing electromagnetic interference(EMI). For real-world inductor applications, these parasitic parameters may be as important as the inductance.

## 2.2.7 Applications

Inductors are used extensively in analog circuits and signal processing. Applications range from the use of large inductors in power supplies, which in conjunction with filter capacitors remove ripple which is a multiple of the mains frequency (or the switching frequency for switched-mode power supplies) from the direct current output, to the small inductance of the ferrite bead or torusinstalled around a cable to prevent radio frequency interference from being transmitted down the wire. Inductors are used as the energy storage device in many switched-mode power supplies to produce DC current. The inductor supplies energy to the circuit to keep current flowing during the "off" switching periods and enables topographies where the output voltage is higher than the input voltage.

A tuned circuit, consisting of an inductor connected to a capacitor, acts as a resonator for oscillating current. Tuned circuits are widely used in radio frequency equipment such as radio transmitters and receivers, as narrow bandpass filters to select a single frequency from a composite signal, and in electronic oscillators to generate sinusoidal signals.

Inductors are also employed in electrical transmission systems, where they are used to limit switching currents and fault currents. In this field, they are more commonly referred to as reactors.

Inductors have parasitic effects which cause them to depart from ideal behavior. They create and suffer from electromagnetic interference (EMI). Their physical size prevents them from being integrated on semiconductor chips. So the use of inductors is declining in modern electronic devices, particularly compact portable devices. Real inductors are increasingly being replaced by active circuits such as the gyrator which can synthesize inductance using capacitors.

## 2.2.8 Inductor construction

An inductor usually consists of a coil of conducting material, typically insulated copper wire, wrapped around a core either of plastic (to create an air-core inductor) or of a ferromagnetic (or ferrimagnetic) material; the latter is called an "iron core" inductor. Since power inductors require high induction levels, high permeability and low saturation points in the core materials are not ideal. The high permeability of the ferromagnetic core increases the magnetic field and confines it closely to the inductor, thereby increasing the inductance. Low frequency inductors are constructed like transformers, with cores of electrical steel laminated to prevent eddy currents. 'Soft' ferrites are widely used for cores above audio frequencies, since they do not cause the large energy losses at high frequencies that ordinary iron alloys do. Inductors come in many shapes. Some inductors have an adjustable core, which enables changing of the inductance. Inductors used to block very high frequencies are sometimes made by stringing a ferrite bead on a wire.

Small inductors can be etched directly onto a printed circuit board by laying out the trace in a spiral pattern. Some such planar inductors use a planar core. Small value inductors can also be built on integrated circuits using the same processes that are used to make transistors. Aluminium interconnect is typically used, laid out in a spiral coil pattern. However, the small dimensions limit the inductance, and it is far more common to use a circuit called a *gyrator* that uses a capacitor and active components to behave similarly to an inductor. Regardless of the design, because of the low inductances and low power dissipation on-die inductors allow, they're currently only commercially used for high frequency RF circuits.

# 2.2.9 Types

## 2.2.9.1 Air-core inductor

The term air core coil describes an inductor that does not use a magnetic core made of a ferromagnetic material. The term refers to coils wound on plastic, ceramic, or other nonmagnetic forms, as well as those that have only air inside the windings. Air core coils have lower inductance than ferromagnetic core coils, but are often used at high frequencies because they are free from energy losses called core losses that occur in ferromagnetic cores, which increase with frequency. A side effect that can occur in air core coils in which the winding is not rigidly supported on a form is 'microphony': mechanical vibration of the windings can cause variations in the inductance.

## 2.2.9.2 Radio-frequency inductor

At high frequencies, particularly radio frequencies (RF), inductors have higher resistance and other losses. In addition to causing power loss, in resonant circuits this can reduce the Q factor of the circuit, broadening the bandwidth. In RF inductors, which are mostly air core types, specialized construction techniques are used to minimize these losses. The losses are due to these effects:

### Skin effect

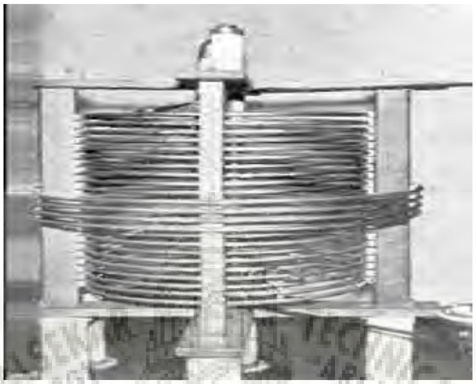
The resistance of a wire to high frequency current is higher than its resistance to direct current because of skin effect. Radio frequency alternating current does not penetrate far into the body of a conductor but travels along its surface. For example, at 6 MHz the skin depth of copper wire is about 0.001 inches (25 μm); most of the current is within this depth of the surface. Therefore, in a solid wire, the interior portion of the wire may carry little current, effectively increasing its resistance.

### Proximity effect

Another similar effect that also increases the resistance of the wire at high frequencies is proximity effect, which occurs in parallel wires that lie close to each other. The individual magnetic field of adjacent turns induces eddy currents in the wire of the coil, which causes the current in the conductor to be concentrated in a thin strip on the side near the adjacent wire. Like skin effect, this reduces the effective cross-sectional area of the wire conducting current, increasing its resistance.

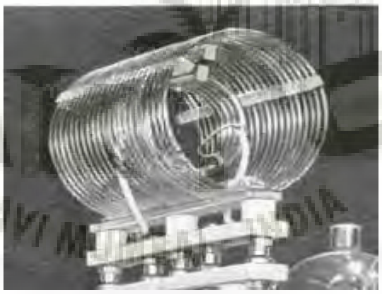
## Dielectric losses

The high frequency electric field near the conductors in a tank coil can cause the motion of polar molecules in nearby insulating materials, dissipating energy as heat. So coils used for tuned circuits are often not wound on coil forms but are suspended in air, supported by narrow plastic or ceramic strips.



## Parasitic capacitance

The capacitance between individual wire turns of the coil, called parasitic capacitance, does not cause energy losses but can change the behavior of the coil. Each turn of the coil is at a slightly different potential, so the electric field between neighboring turns stores charge on the wire, so the coil acts as if it has a capacitor in parallel with it. At a high enough frequency this capacitance can resonate with the inductance of the coil forming a tuned circuit, causing the coil to become self-resonant.



To reduce parasitic capacitance and proximity effect, high Q RF coils are constructed to avoid having many turns lying close together, parallel to one another. The windings of RF coils are often limited to a single layer, and the turns are spaced apart. To reduce resistance due to skin effect, in high-power inductors such as those used in transmitters the windings are sometimes made of a metal strip or tubing which has a larger surface area, and the surface is silver-plated.

### 2.2.9.3 Ferrite-core inductor

For higher frequencies, inductors are made with cores of ferrite. Ferrite is a ceramic ferrimagnetic material that is nonconductive, so eddy currents cannot flow within it. The formulation of ferrite is $xxFe_2O_4$ where xx represents various metals. For inductor cores soft ferrites are used, which have low coercivity and thus low hysteresis losses.

### 2.2.9.4 Toroidal-core inductor

In an inductor wound on a straight rod-shaped core, the magnetic field lines emerging from one end of the core must pass through the air to re-enter the core at the other end. This reduces the field, because much of the magnetic field path is in air rather than the higher permeability core material and is a source of electromagnetic interference. A higher magnetic field and inductance can be achieved by forming the core in a closed magnetic circuit. The magnetic field lines form closed loops within the core without leaving the core material. The shape often used is a toroidal or doughnut-shaped ferrite core. Because of their symmetry, toroidal cores allow a minimum of the magnetic flux to escape outside the core (called *leakage flux*), so they radiate less electromagnetic interference than other shapes. Toroidal core coils are manufactured of various materials, primarily ferrite, powdered iron and laminated cores.

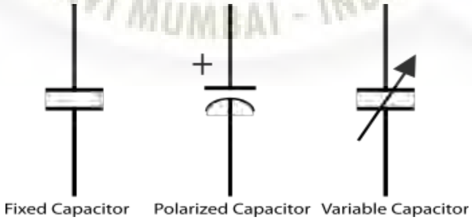
# 2.3 Capacitor

A **capacitor** is a passive two-terminal electronic component that stores electrical energy in an electric field. The effect of a capacitor is known as capacitance. While some capacitance exists between any two electrical conductors in proximity in a circuit, a capacitor is a component designed to add capacitance to a circuit. The capacitor was originally known as a **condenser** or **condensator**. The original name is still widely used in many languages, but not commonly in English.

The physical form and construction of practical capacitors vary widely and many capacitor types are in common use. Most capacitors contain at least two electrical conductors often in the form of metallic plates or surfaces separated by a dielectric medium. A conductor may be a foil, thin film, sintered bead of metal, or an electrolyte. The non conducting dielectric acts to increase the capacitor's charge capacity. Materials commonly used as dielectrics include glass, ceramic, plastic film, paper, mica, and oxide layers. Capacitors are widely used as parts of electrical circuits in many common electrical devices. Unlike a resistor, an ideal capacitor does not dissipate energy.

When two conductors experience a potential difference, for example, when a capacitor is attached across a battery, an electric field develops across the dielectric, causing a net positive charge to collect on one plate and net negative charge to collect on the other plate. No current actually flows through the dielectric, however, there is a flow of charge through the source circuit. If the condition is maintained sufficiently long, the current through the source circuit ceases. However, if a time-varying voltage is applied across the leads of the capacitor, the source experiences an ongoing current due to the charging and discharging cycles of the capacitor.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass. In analog filter networks, they smooth the output of power supplies. In resonant circuits they tune radios to particular frequencies. In electric power transmission systems, they stabilize voltage and power flow. The property of energy storage in capacitors was exploited as dynamic memory in early digital computers.



## 2.3.1 Theory of operation

A capacitor consists of two conductors separated by a non-conductive region. The non-conductive region can either be a vacuum or an electrical insulator material known as a dielectric. Examples of dielectric media are glass, air, paper, plastic, ceramic, and even a semiconductor depletion region chemically identical to the conductors. From Coulomb's law a charge on one conductor will exert a force on the charge carriers within the other conductor, attracting opposite polarity charge and repelling like polarity charges, thus an opposite polarity charge will be induced on the surface of the other conductor. The conductors thus hold equal and opposite charges on their facing surfaces, and the dielectric develops an electric field.

An ideal capacitor is characterized by a constant capacitance C, in farads in the SI system of units, defined as the ratio of the positive or negative charge Q on each conductor to the voltage V between them:

**C = Q / V**

A capacitance of one farad (F) means that one coulomb of charge on each conductor causes a voltage of one volt across the device. Because the conductors (or plates) are close together, the opposite charges on the conductors attract one another due to their electric fields, allowing the capacitor to store more charge for a given voltage than when the conductors are separated, yielding a larger capacitance.

In practical devices, charge build-up sometimes affects the capacitor mechanically, causing its capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

**C = dQ/ dV**

## 2.3.1.1 Parallel-plate capacitor

The simplest model capacitor consists of two thin parallel conductive plates each with an area of A separated by a uniform gap of thickness d filled with a dielectric with permittivity ε. It is assumed the gap d is much smaller than the dimensions of the plates. This model applies well to many practical capacitors which are constructed of metal sheets separated by a thin layer of insulating dielectric, since manufacturers try to keep the dielectric very uniform in thickness to avoid thin spots which can cause failure of the capacitor.

Since the separation between the plates is uniform over the plate area, the electric field between the plates E is constant, and directed perpendicularly to the plate surface, except for an area near the edges of the plates where the field decreases because the electric field lines "bulge" out of the sides of the capacitor. This "fringing field" area is approximately the same width as the plate separation, d, and assuming d is small compared to the plate dimensions, it is small enough to be ignored. Therefore, if a charge of +Q is placed on one plate and -Q on the other plate, the charge on each plate will be spread evenly in a surface charge layer of constant charge density σ = + Q / A coulombs

$$V = \int_0^d E(z)\,\mathrm{d}z = Ed = \frac{\sigma}{\varepsilon}d = \frac{Qd}{\varepsilon A}$$

The capacitance is defined as $C = Q/V$. Substituting $V$ above into this equation

$$\boxed{C = \frac{\varepsilon A}{d}}$$

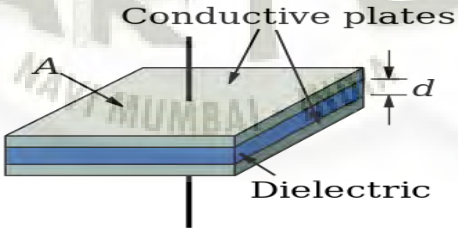
per square meter, on the inside surface of each plate. From Gauss's law the magnitude of the electric field between the plates is E= σ / ε. The voltage V between the plates is defined as the line integral of the electric field over a line from one plate to another

Therefore, in a capacitor the highest capacitance is achieved with a high permittivity dielectric material, large plate area, and small separation between the plates.

Since the area A of the plates increases with the square of the linear dimensions and the separation d increases linearly, the capacitance scales with the linear dimension of a capacitor ($C \propto L$ ), or as the cube root of the volume.

A parallel plate capacitor can only store a finite amount of energy before dielectric breakdown occurs. The capacitor's dielectric material has a dielectric strength $U_d$ which sets the capacitor's breakdown voltage at $V = V_{bd} = U_d d$. The maximum energy that the capacitor can store is therefore

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon A}{d}(U_d d)^2 = \frac{1}{2}\varepsilon A d U_d^2$$



## 2.3.1.2 Energy stored in a capacitor

To increase the charge and voltage on a capacitor, work must be done by an external power source to move charge from the negative to the positive plate against the opposing force of the electric field. If the voltage on the capacitor is V the work dW required to move a small increment of charge dq from the negative to the positive plate is dW = V dq The energy is stored in the increased electric field between the plates. The total

$$W = \int_0^Q V(q)\mathrm{d}q = \int_0^Q \frac{q}{C}\mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}VQ = \frac{1}{2}CV^2$$

energy W stored in a capacitor (expressed in Joule) is equal to the total work done in establishing the electric field from an uncharged state.

where Q is the charge stored in the capacitor, V is the voltage across the capacitor, and C is the capacitance. This potential energy will remain in the capacitor until the charge is removed. If charge is allowed to move back from the positive to the negative plate, for example by connecting a circuit with resistance between the plates, the charge moving under the influence of the electric field will do work on the external circuit.

If the gap between the capacitor plates d is constant, as in the parallel plate model above, the electric field between the plates will be uniform (neglecting fringing fields) and will have a constant value E=V/d In this case the stored energy can be calculated from the electric field strength

$$W=\frac{1}{2}CV^2=\frac{1}{2}\frac{\epsilon A}{d}(Ed)^2=\frac{1}{2}\epsilon AdE^2=\frac{1}{2}\epsilon E^2(\text{volume of electric field})$$

The last formula above is equal to the energy density per unit volume in the electric field multiplied by the volume of field between the plates, confirming that the energy in the capacitor is stored in its electric field.

## 2.3.1.3 Current–voltage relation

The current I(t) through any component in an electric circuit is defined as the rate of flow of a charge Q(t) passing through it, but actual charges—electrons—cannot pass through the dielectric layer of a capacitor. Rather, one electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage, as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $V(t_0)$. This is the integral form of the capacitor equation:

$$V(t)=\frac{Q(t)}{C}=\frac{1}{C}\int_{t_0}^{t}I(\tau)\mathrm{d}\tau+V(t_0)$$

Taking the derivative of this and multiplying by *C* yields the derivative form:[25]

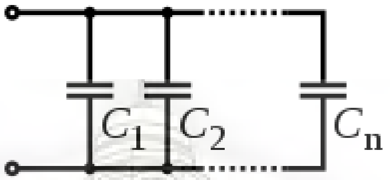
$$I(t)=\frac{\mathrm{d}Q(t)}{\mathrm{d}t}=C\frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

The dual of the capacitor is the inductor, which stores energy in a magnetic field rather than an electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing C with the inductance L.

## 2.3.1.4 Circuit analysis

### For capacitors in parallel

Capacitors in a parallel configuration each have the same applied voltage. Their capacitances add up. Charge is apportioned among them by size. Using the schematic diagram to visualize parallel plates, it is apparent that each capacitor contributes to the total surface area.

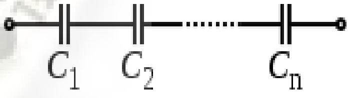


$$C_{\text{eq}} = \sum_i C_i = C_1 + C_2 + \cdots + C_n$$

### For capacitors in series

Connected in series, the schematic diagram reveals that the separation distance, not the plate area, adds up. The capacitors each store instantaneous charge build-up equal to that of every other capacitor in the series. The total voltage difference from end to end is apportioned to each capacitor according to the inverse of its capacitance. The entire series acts as a capacitor *smaller* than any of its components.

$$\frac{1}{C_{\text{eq}}} = \sum_i \frac{1}{C_i} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$



### Voltage distribution in parallel-to-series networks.

$$(volts)A_{\text{eq}} = A\left(1 - \frac{1}{n+1}\right)$$

$$(volts)B_{1..\text{n}} = \frac{A}{n}\left(1 - \frac{1}{n+1}\right)$$

$$A - B = 0$$

To model the distribution of voltages from a single charged capacitor (A) connected in parallel to a chain of capacitors in series ($B_n$)

**Note:** This is only correct if all capacitance values are equal.

The power transferred in this arrangement is:

$$P = \frac{1}{R} \cdot \frac{1}{n+1} A_{\text{volts}} \left( A_{\text{farads}} + B_{\text{farads}} \right)$$

## 2.3.2 Applications

### 2.3.2.1 Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery, or like other types of rechargeable energy storage system. Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

A capacitor can facilitate conversion of kinetic energy of charged particles into electric energy and store it.

Conventional capacitors provide less than 360 joules per kilogram of specific energy, whereas a conventional alkaline battery has a density of 590 kJ/kg. There is an intermediate solution: Super capacitors, which can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. They are, however, 10 times larger than conventional batteries for a given charge. On the other hand, it has been shown that the amount of charge stored in the dielectric layer of the thin film capacitor can be equal to, or can even exceed, the amount of charge stored on its plates.

In car audio systems, large capacitors store energy for the amplifier to use on demand. Also, for a flash tube, a capacitor is used to hold the high voltage

### 2.3.2.2 Pulsed power and weapons

Groups of large, specially constructed, low-inductance high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many pulsed powerapplications. These include electromagnetic forming, Marx generators, pulsed lasers (especially TEA lasers), pulse forming networks, radar, fusion research, and particle accelerators.

Large capacitor banks (reservoir) are used as energy sources for the exploding-bridgewire detonators or slapper detonators in nuclear weapons and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic armour and electromagnetic railguns and coilguns.

### 2.3.2.3 Power conditioning

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in car audio applications, when a stiffening capacitor compensates for the inductance and resistance of the leads to the lead-acid car battery.

### 2.3.2.4 Power factor correction

n electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load. Usually, the values of these capacitors are not given in farads but rather as a reactive power in volt-amperes reactive (var). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

# CHAPTER 3 : TRANSFORMERS

## 3.1 Normal Transformer

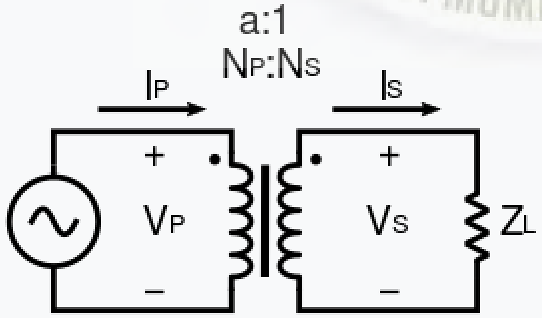
A **transformer** is a static electrical device that transfers electrical energy between two or more circuits. A varying current in one coil of the transformer produces a varying magnetic flux, which, in turn, induces a varying electromotive force across a second coil wound around the same core. Electrical energy can be transferred between the two coils, without a metallic connection between the two circuits. Faraday's law of induction discovered in 1831 described the induced voltage effect in any coil due to changing magnetic flux encircled by the coil.

Transformers are used for increasing or decreasing the alternating voltages in electric power applications, and for coupling the stages of signal processing circuits.

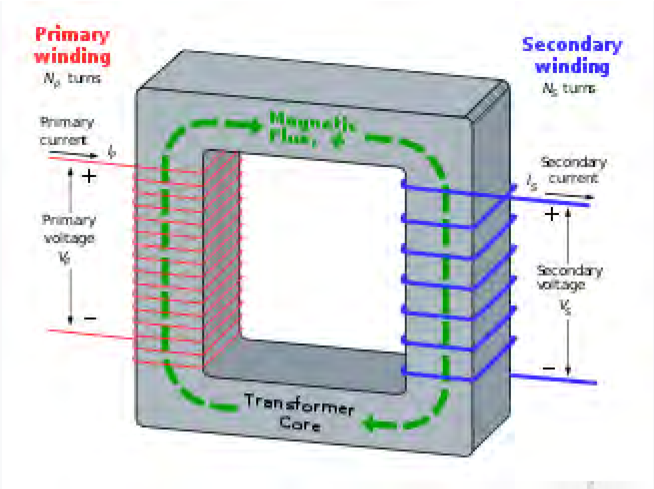
Since the invention of the first constant-potential transformer in 1885, transformers have become essential for the transmission, distribution, and utilization of alternating current electric power. A wide range of transformer designs is encountered in electronic and electric power applications. Transformers range in size from RF transformers less than a cubic centimeter in volume, to units weighing hundreds of tons used to interconnect the power grid.

### 3.1.1 Ideal transformer

An ideal transformer is a theoretical linear transformer that is lossless and perfectly coupled. Perfect coupling implies infinitely high core magnetic permeability and winding inductances and zero net magnetomotive force (i.e. $i_p n_p - i_s n_s = 0$).



Ideal transformer connected with source $V_P$ on primary and load impedance $Z_L$ on secondary, where $0 < Z_L < \infty$.



Ideal transformer and induction law

A varying current in the transformer's primary winding attempts to create a varying magnetic flux in the transformer core, which is also encircled by the secondary winding. This varying flux at the secondary winding induces a varying electromotive force (EMF, voltage) in the secondary winding due to electromagnetic induction and the secondary current so produced creates a flux equal and opposite to that produced by the primary winding, in accordance with Lenz's law.

The windings are wound around a core of infinitely high magnetic permeability so that all of the magnetic flux passes through both the primary and secondary windings. With a voltage source connected to the primary winding and load impedance connected to the secondary winding, the transformer currents flow in the indicated directions and the core magnetomotive force cancels to zero.

According to Faraday's law, since the same magnetic flux passes through both the primary and secondary windings in an ideal transformer, a voltage is induced in each winding proportional to its number of windings. Thus, referring to the equations shown in the sidebox at right, according to Faraday's law, we have primary and secondary winding voltages defined by eq. 1 & eq. 2, respectively. The primary EMF is sometimes termed counter EMF. This is in accordance with Lenz's law, which states that induction of EMF always opposes development of any such change in magnetic field.

The transformer winding voltage ratio is thus shown to be directly proportional to the winding turns ratio according to eq. 3. However, some sources use the inverse definition.

According to the law of conservation of energy, any load impedance connected to the ideal transformer's secondary winding results in conservation of apparent, real and reactive power consistent with eq. 4.

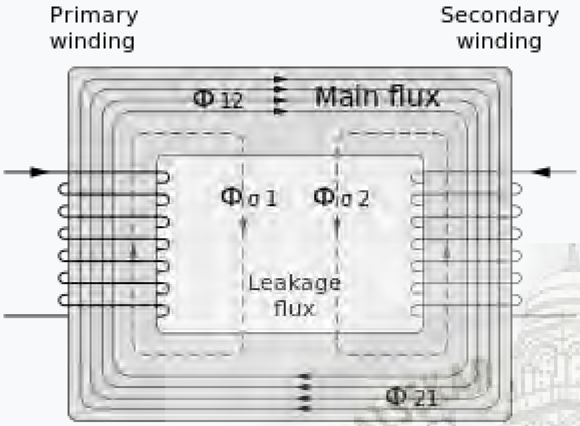
The ideal transformer identity shown in eq. 5 is a reasonable approximation for the typical commercial transformer, with voltage ratio and winding turns ratio both being inversely proportional to the corresponding current ratio.

By Ohm's law and the ideal transformer identity:

- the secondary circuit load impedance can be expressed as eq. 6

- the apparent load impedance *referred* to the primary circuit is derived in eq. 7 to be equal to the turns ratio squared times the secondary circuit load impedance.[16][17]

## 3.1.2 Real transformer



Leakage flux of a transformer

*Deviations from ideal transformer*

The ideal transformer model neglects the following basic linear aspects of real transformers:

(a) Core losses, collectively called magnetizing current losses, consisting of

- Hysteresis losses due to nonlinear magnetic effects in the transformer core, and
- Eddy current losses due to joule heating in the core that are proportional to the square of the transformer's applied voltage.

(b) Unlike the ideal model, the windings in a real transformer have non-zero resistances and inductances associated with:

- Joule losses due to resistance in the primary and secondary windings[18]
- Leakage flux that escapes from the core and passes through one winding only resulting in primary and secondary reactive impedance.

(c) similar to an inductor, parasitic capacitance and self-resonance phenomenon due to the electric field distribution. Three kinds of parasitic capacitance are usually considered and the closed-loop equations are provided [19]

- Capacitance between adjacent turns in any one layer;
- Capacitance between adjacent layers;
- Capacitance between the core and the layer(s) adjacent to the core;

Inclusion of capacitance into the transformer model is complicated, and is rarely attempted; the ‘real’ transformer model’s equivalent circuit does not include parasitic capacitance. However, the capacitance effect can be measured by comparing open-circuit inductance, i.e. the inductance of a primary winding when the secondary circuit is open, to a short-circuit inductance when the secondary winding is shorted.

*Leakage flux*

The ideal transformer model assumes that all flux generated by the primary winding links all the turns of every winding, including itself. In practice, some flux traverses paths that take it outside the windings.Such flux is termed *leakage flux*, and results in leakage inductance in series with the mutually coupled transformer windings. Leakage flux results in energy being alternately stored in and discharged from the magnetic fields with each cycle of the power supply. It is not directly a power loss, but results in inferior voltage regulation, causing the secondary voltage not to be directly proportional to the primary voltage, particularly under heavy load.Transformers are therefore normally designed to have very low leakage inductance.

In some applications increased leakage is desired, and long magnetic paths, air gaps, or magnetic bypass shunts may deliberately be introduced in a transformer design to limit the short-circuit current it will supply.[12] Leaky transformers may be used to supply loads that exhibit negative resistance, such as electric arcs, mercury- and sodium- vapor lamps and neon signs or for safely handling loads that become periodically short-circuited such as electric arc welders.

Air gaps are also used to keep a transformer from saturating, especially audio-frequency transformers in circuits that have a DC component flowing in the windings. A saturable reactor exploits saturation of the core to control alternating current.

Knowledge of leakage inductance is also useful when transformers are operated in parallel. It can be shown that if the percent impedance[i] and associated winding leakage reactance-to-resistance ($X/R$) ratio of two transformers were hypothetically exactly the same, the transformers would share power in proportion to their respective volt-ampere ratings (e.g. 500 kVA unit in parallel with 1,000 kVA unit, the larger unit would carry twice the current). However, the impedance tolerances of commercial transformers are significant. Also, the Z impedance and X/R ratio of different capacity transformers tends to vary, corresponding 1,000 kVA and 500 kVA units' values being, to illustrate, respectively, $Z \approx 5.75\%$, $X/R \approx 3.75$ and $Z \approx 5\%$, $X/R \approx 4.75$.

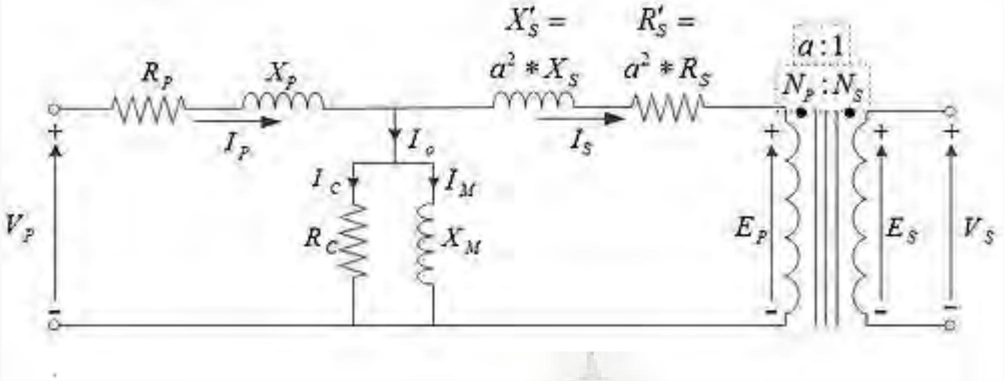
*Equivalent circuit*

Referring to the diagram, a practical transformer's physical behavior may be represented by an equivalent circuit model, which can incorporate an ideal transformer.

Winding joule losses and leakage reactances are represented by the following series loop impedances of the model:

- Primary winding: $R_P$, $X_P$
- Secondary winding: $R_S$, $X_S$.

In normal course of circuit equivalence transformation, $R_S$ and $X_S$ are in practice usually referred to the primary side by multiplying these impedances by the turns ratio squared, $(N_P/N_S)^2 = a^2$.



Real transformer equivalent circuit

Core loss and reactance is represented by the following shunt leg impedances of the model:

- Core or iron losses: $R_C$
- Magnetizing reactance: $X_M$.

$R_C$ and $X_M$ are collectively termed the *magnetizing branch* of the model.

Core losses are caused mostly by hysteresis and eddy current effects in the core and are proportional to the square of the core flux for operation at a given frequency. The finite permeability core requires a magnetizing current $I_M$ to maintain mutual flux in the core. Magnetizing current is in phase with the flux, the relationship between the two being non-linear due to saturation effects. However, all impedances of the equivalent circuit shown are by definition linear and such non-linearity effects are not typically reflected in transformer equivalent circuits. With sinusoidal supply, core flux lags the induced EMF by 90°. With open-circuited secondary winding, magnetizing branch current $I_0$ equals transformer no-load current.[25]

Instrument transformer, with polarity dot and X1 markings on LV side terminal

The resulting model, though sometimes termed 'exact' equivalent circuit based on linearity assumptions, retains a number of approximations. Analysis may be simplified by assuming that magnetizing branch impedance is relatively high and relocating the branch to the left of the primary impedances. This introduces error but allows combination of primary and referred secondary resistances and reactances by simple summation as two series impedances.

Transformer equivalent circuit impedance and transformer ratio parameters can be derived from the following tests: open-circuit test, short-circuit test, winding resistance test, and transformer ratio test.

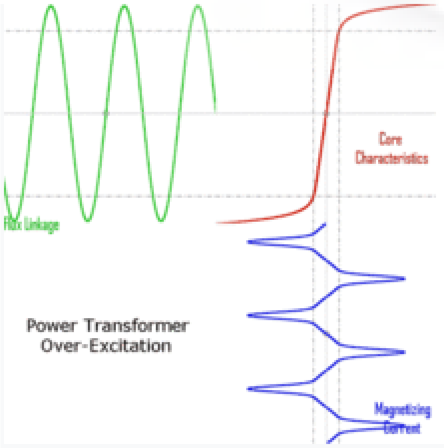
### 3.1.2.1 Basic transformer parameters

A dot convention is often used in transformer circuit diagrams, nameplates or terminal markings to define the relative polarity of transformer windings. Positively increasing instantaneous current entering the primary winding's ‘dot’ end induces positive polarity voltage exiting the secondary winding's ‘dot’ end.

Three-phase transformers used in electric power systems will have a nameplate that indicate the phase relationships between their terminals. This may be in the form of a phasordiagram, or using an alpha-numeric code to show the type of internal connection (wye or delta) for each winding.

Effect of frequency

The EMF of a transformer at a given flux increases with frequency.[18] By operating at higher frequencies, transformers can be physically more compact because a given core is able to transfer more power without reaching saturation and fewer turns are needed to achieve the same impedance. However, properties such as core loss and conductor skin effect also increase with frequency. Aircraft and military equipment employ 400 Hz power supplies which reduce core and winding weight.[35] Conversely, frequencies used for some railway electrification systems were much lower (e.g. 16.7 Hz and 25 Hz) than normal utility frequencies (50–60 Hz) for historical reasons concerned mainly with the limitations of early electric traction motors. Consequently, the transformers used to step-down the high overhead line voltages (e.g. 15 kV) were much larger and heavier for the same power rating than those required for the higher frequencies.



Power transformer over-excitation condition caused by decreased frequency; flux (green), iron core's magnetic characteristics (red) and magnetizing current (blue).

Operation of a transformer at its designed voltage but at a higher frequency than intended will lead to reduced magnetizing current. At a lower frequency, the magnetizing current will increase. Operation of a large transformer at other than its design frequency may require assessment of voltages, losses, and cooling to establish if safe operation is practical. For example, transformers may need to be equipped with 'volts per hertz' over-excitation, ANSI function 24, relays to protect the transformer from overvoltage at higher than rated frequency.

One example is in traction transformers used for electric multiple unit and high-speed train service operating across regions with different electrical standards. The converter equipment and traction transformers have to accommodate different input frequencies and voltage (ranging from as high as 50 Hz down to 16.7 Hz and rated up to 25 kV) while being suitable for multiple AC asynchronous motor and DC converters and motors with varying harmonics mitigation filtering requirements.

At much higher frequencies the transformer core size required drops dramatically: a physically small transformer can handle power levels that would require a massive iron core at mains frequency. The development of switching power semiconductor devices and complex integrated circuits made switch-mode power supplies viable, to generate a high frequency from a much lower one (or DC), change the voltage level with a small transformer, and, if necessary, rectify the changed voltage.

Large power transformers are vulnerable to insulation failure due to transient voltages with high-frequency components, such as caused in switching or by lightning.

## 3.1.2.2 Energy losses

Transformer energy losses are dominated by winding and core losses. Transformers' efficiency tends to improve with increasing transformer capacity. The efficiency of typical distribution transformers is between about 98 and 99 percent.

As transformer losses vary with load, it is often useful to tabulate no-load loss, full-load loss, half-load loss, and so on. Hysteresis and eddy current losses are constant at all load levels and dominate overwhelmingly without load, while variable winding joule losses dominating increasingly as load increases. The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply. Designing energy efficient transformers for lower loss requires a larger core, good-quality silicon steel, or even amorphous steel for the core and thicker wire, increasing initial cost. The choice of construction represents a trade-off between initial cost and operating cost.[41]

Transformer losses arise from:

**Winding joule losses**

Current flowing through a winding's conductor causes joule heating. As frequency increases, skin effect and proximity effect causes the winding's resistance and, hence, losses to increase.

**Core losses**

**Hysteresis losses**

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. According to Steinmetz's formula, the heat energy due to hysteresis is given by

where, *f* is the frequency, *η* is the hysteresis coefficient and $\beta_{\max}$ is the maximum flux density, the empirical exponent of which varies from about 1.4 to 1.8 but is often given as 1.6 for iron.

**Eddy current losses**

Eddy currents are produced in the metal transformer core and cause heating of the core. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness.[41] Eddy current losses can be reduced by making the core of a stack of plates electrically insulated from each other, rather than a solid block; all transformers operating at low frequencies use laminated or similar cores.

**Magnetostriction related transformer hum**

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction, the frictional energy of which produces an audible noise known as mains hum or transformer hum. This transformer hum is especially objectionable in transformers supplied at power frequencies[o] and in high-frequency flyback transformers associated with television CRTs.

**Stray losses**

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat.

In addition to magnetostriction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. This energy incites vibration transmission in interconnected metalwork, thus amplifying audible transformer hum.

## 3.1.3 Construction

### 3.1.3.1 Cores

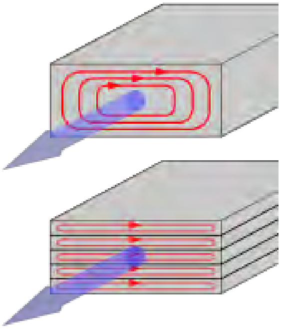
Closed-core transformers are constructed in 'core form' or 'shell form'. When windings surround the core, the transformer is core form; when windings are surrounded by the core, the transformer is shell form.Shell form design may be more prevalent than core form design for distribution transformer applications due to the relative ease in stacking the core around winding coils. Core form design tends to, as a general rule, be more economical, and therefore more prevalent, than shell form design for high voltage power transformer applications at the lower end of their voltage and power rating ranges (less than or equal to, nominally, 230 kV or 75 MVA). At higher voltage and power ratings, shell form transformers tend to be more prevalent. Shell form design tends to be preferred for extra-high voltage and higher MVA applications because, though more labor-intensive to manufacture, shell form transformers are characterized as having inherently better kVA-to-weight ratio, better short-circuit strength characteristics and higher immunity to transit damage.

*Laminated steel cores*

Laminated core transformer showing edge of laminations at top of photo

Transformers for use at power or audio frequencies typically have cores made of high permeability silicon steel. The steel has a permeability many times that of free space and the core thus serves to greatly reduce the magnetizing current and confine the flux to a path which closely couples the windings. Early transformer developers soon realized that cores constructed from solid iron resulted in prohibitive eddy current losses, and their designs mitigated this effect with cores consisting of bundles of insulated iron wires. Later designs constructed the core by stacking layers of thin steel laminations, a principle that has remained in use. Each lamination is insulated from its neighbors by a thin non-conducting layer of insulation. The transformer universal EMF equation implies an acceptably large core cross-sectional area to avoid saturation.

The effect of laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude. Thinner laminations reduce losses, but are more laborious and expensive to construct. Thin laminations are generally used on high-



frequency transformers, with some of very thin steel laminations able to operate up to 10 kHz.

One common design of laminated core is made from interleaved stacks of E-shaped steel sheets capped with I-shaped pieces, leading to its name of 'E-I transformer'.[57] Such a design tends to exhibit more losses, but is very economical to manufacture. The cut-core or C-core type is made by winding a steel strip around a rectangular form and then bonding the layers together. It is then cut in two, forming two C shapes, and the core assembled by binding the two C halves together with a steel strap.They have the advantage that the flux is always oriented parallel to the metal grains, reducing reluctance.

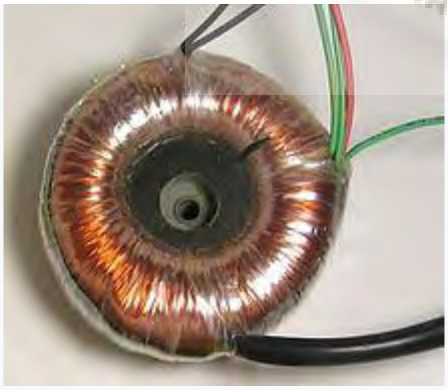
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied AC waveform. Overcurrent protection devices such as fuses must be selected to allow this harmless inrush to pass. On transformers connected to long, overhead power transmission lines, induced currents due to geomagnetic disturbances during solar storms can cause saturation of the core and operation of transformer protection devices.

Distribution transformers can achieve low no-load losses by using cores made with low-loss high-permeability silicon steel or amorphous (non-crystalline) metal alloy. The higher initial cost of the core material is offset over the life of the transformer by its lower losses at light load.[60]

Solid cores

Powdered iron cores are used in circuits such as switch-mode power supplies that operate above mains frequencies and up to a few tens of kilohertz. These materials combine high magnetic permeability with high bulk electrical resistivity. For frequencies extending beyond the VHF band, cores made from non-conductive magnetic ceramic materials called ferrites are common.[57] Some radio-frequency transformers also have movable cores (sometimes called 'slugs') which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

Toroidal cores



Small toroidal core transformer

Toroidal transformers are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steelor permalloy wound into a coil, powdered iron, or ferrite. A strip construction ensures that the grain boundaries are optimally aligned, improving the transformer's efficiency by reducing the core's reluctance. The closed ring shape eliminates air gaps inherent in the construction of an E-I core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed and provides screening to minimize the core's magnetic field from generating electromagnetic interference.

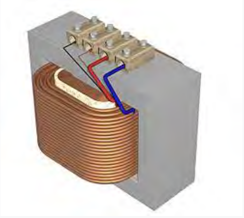
Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity (see Classification parameters below). Because of the lack of a residual gap in the magnetic path, toroidal transformers also tend to exhibit higher inrush current, compared to laminated E-I types.

Ferrite toroidal cores are used at higher frequencies, typically between a few tens of kilohertz to hundreds of megahertz, to reduce losses, physical size, and weight of inductive components. A drawback of toroidal transformer construction is the higher labor cost of winding. This is because it is necessary to pass the entire length of a coil winding through the core aperture each time a single turn is added to the coil. As a consequence, toroidal transformers rated more than a few kVA are uncommon. Relatively few toroids are offered with power ratings above 10 kVA, and practically none above 25 kVA. Small distribution transformers may achieve some of the benefits of a toroidal core by splitting it and forcing it open, then inserting a bobbin containing primary and secondary windings.

Air cores

A transformer can be produced by placing the windings near each other, an arrangement termed an "air-core" transformer. An air-core transformer eliminates loss due to hysteresis in the core material. The magnetizing inductance is drastically reduced by the lack of a magnetic core, resulting in large magnetizing currents and losses if used at low frequencies. Air-core transformers are unsuitable for use in power distribution, but are frequently employed in radio-frequency applications. Air cores are also used for resonant transformers such as Tesla coils, where they can achieve reasonably low loss despite the low magnetizing inductance.

### 3.1.3.2 Windings



Windings are usually arranged concentrically to minimize flux leakage.

The electrical conductor used for the windings depends upon the application, but in all cases the individual turns must be electrically insulated from each other to ensure that the current travels throughout every turn. For small transformers, in which currents are low and the potential difference between adjacent turns is small, the coils are often wound from enamelled magnet wire. Larger power transformers may be wound with copper rectangular strip conductors insulated by oil-impregnated paper and blocks of pressboard.

High-frequency transformers operating in the tens to hundreds of kilohertz often have windings made of braided Litz wire to minimize the skin-effect and proximity effect losses. Large power transformers use multiple-stranded conductors as well, since even at low power frequencies non-uniform distribution of current would otherwise exist in high-current windings. Each strand is individually insulated, and the strands are arranged so that at certain points in the winding, or throughout the whole winding, each portion occupies different relative positions in the complete conductor. The transposition equalizes the current flowing in each strand of the conductor, and reduces eddy current losses in the winding itself. The stranded conductor is also more flexible than a solid conductor of similar size, aiding manufacture.

The windings of signal transformers minimize leakage inductance and stray capacitance to improve high-frequency response. Coils are split into sections, and those sections interleaved between the sections of the other winding.

Power-frequency transformers may have *taps* at intermediate points on the winding, usually on the higher voltage winding side, for voltage adjustment. Taps may be manually reconnected, or a manual or automatic switch may be provided for changing taps. Automatic on-load tap changers are used in electric power transmission or distribution, on equipment such as arc furnace transformers, or for automatic voltage regulators for sensitive loads. Audio-frequency transformers, used for the distribution of audio to public address loudspeakers, have taps to allow adjustment of impedance to each speaker. A center-tapped transformer is often used in the output stage of an audio power amplifier in a push-pull circuit. Modulation transformers in AM transmitters are very similar.

### Insulation

Insulation must be provided between the individual turns of the windings, between the windings, between windings and core, and at the terminals of the winding.

Inter-turn insulation of small transformers may be a layer of insulating varnish on the wire. Layer of paper or polymer films may be inserted between layers of windings, and between primary and secondary windings. A transformer may be coated or dipped in a polymer resin to improve the strength of windings and protect them from moisture or corrosion. The resin may be impregnated into the winding insulation using combinations of vacuum and pressure during the coating process, eliminating all air voids in the winding. In the limit, the entire coil may be placed in a mold, and resin cast around it as a solid block, encapsulating the windings.

Large oil-filled power transformers use windings wrapped with insulating paper, which is impregnated with oil during assembly of the transformer. Oil-filled transformers use highly refined mineral oil to insulate and cool the windings and core. Construction of oil-filled transformers requires that the insulation covering the windings be thoroughly dried of residual moisture before the oil is introduced. Drying may be done by circulating hot air around the core, by circulating externally heated transformer oil, or by vapor-phase drying (VPD) where an evaporated solvent transfers heat by condensation on the coil and core. For small transformers, resistance heating by injection of current into the windings is used.

### 3.1.4 Applications

Transformer at the Limestone Generating Station in Manitoba, Canada

Since the high voltages carried in the wires are significantly greater than what is needed in-home, transformers are also used extensively in electronic products to decrease (or step-down) the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage. Transformers are used to increase (or step-up) voltage before transmitting electrical energy over long distances through wires. Wires have resistance which loses energy through joule heating at a rate corresponding to square of the current. By transforming power to a higher voltage transformers enable economical transmission of power and distribution. Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand. All but a tiny fraction of the world's electrical power has passed through a series of transformers by the time it reaches the consumer.

Signal and audio transformers are used to couple stages of amplifiers and to match devices such as microphones and record players to the input of amplifiers. Audio transformers allowed telephone circuits to carry on a two-way conversation over a single pair of wires. A baluntransformer converts a signal that is referenced to ground to a signal that has balanced voltages to ground, such as between external cables and internal circuits. Transformers made to medical grade standards isolate the users from the direct current. These are found commonly used in conjunction with hospital beds, dentist chairs, and other medical lab equipment.

## 3.2 Pulse transformer

A **pulse transformer** is a transformer that is optimised for transmitting rectangular electrical pulses (that is, pulses with fast rise and fall times and a relatively constant amplitude). Small versions called *signal* types are used in digital logic and telecommunications circuits, often for matching logic drivers to transmission lines. Medium-sized *power* versions are used in power-control circuits such as camera flash controllers. Larger *power* versions are used in the electrical power distribution industry to interface low-voltage control circuitry to the high-voltage gates of power semiconductors. Special high voltage pulse transformers are also used to generate high power pulses for radar, particle accelerators, or other high energy pulsed power applications.[16]

To minimize distortion of the pulse shape, a pulse transformer needs to have low values of leakage inductance and distributed capacitance, and a high open-circuit inductance. In power-type pulse transformers, a low coupling capacitance (between the primary and secondary) is important to protect the circuitry on the primary side from high-powered transients created by the load. For the same reason, high insulation resistance and high breakdown voltage are required. A good transient response is necessary to maintain the rectangular pulse shape at the secondary, because a pulse with slow edges would create switching losses in the power semiconductors.

The product of the peak pulse voltage and the duration of the pulse (or more accurately, the voltage-time integral) is often used to characterise pulse transformers. Generally speaking, the larger this product, the larger and more expensive the transformer.

Pulse transformers by definition have a duty cycle of less than 0.5; whatever energy stored in the coil during the pulse must be "dumped" out before the pulse is fired again.

# CHAPTER 4: SEMICONDUCTOR COMPONENT

## 4.1 Diode

A **diode** is a two-terminal electronic component that conducts current primarily in one direction (asymmetric conductance); it has low (ideally zero) resistance in one direction, and high (ideally infinite) resistance in the other. A diode vacuum tube or **thermionic diode** is a vacuum tube with two electrodes, a heated cathode and a plate, in which electrons can flow in only one direction, from cathode to plate. A **semiconductor diode**, the most common type today, is a crystalline piece of semiconductor material with a p–n junction connected to two electrical terminals. Semiconductor diodes were the first semiconductor electronic devices. The discovery of asymmetric electrical conduction across the contact between a crystalline mineral and a metal was made by German physicist Ferdinand Braun in 1874. Today, most diodes are made of silicon, but other materials such as gallium arsenide and germanium are used.

Close-up view of a silicon diode. The anode is at the right side; the cathode is at the left side (where it is marked with a black band). The square silicon crystal can be seen between the two leads.

### 4.1.1 Main functions

The most common function of a diode is to allow an electric current to pass in one direction (called the diode's forward direction), while blocking it in the opposite direction (the reverse direction). As such, the diode can be viewed as an electronic version of a check valve. This unidirectional behavior is called rectification, and is used to convert alternating current (ac) to direct current (dc). Forms of rectifiers, diodes can be used for such tasks as extracting modulation from radio signals in radio receivers.

However, diodes can have more complicated behavior than this simple on–off action, because of their nonlinear current-voltage characteristics. Semiconductor diodes begin conducting electricity only if a certain threshold voltage or cut-in voltage is present in the forward direction (a state in which the diode is said to be forward-biased). The voltage drop across a forward-biased diode varies only a little with the current, and is a function of temperature; this effect can be used as a temperature sensor or as a voltage reference. Also, diodes' high resistance to current flowing in the reverse direction suddenly drops to a low resistance when the reverse voltage across the diode reaches a value called the breakdown voltage.

A semiconductor diode's current–voltage characteristic can be tailored by selecting the semiconductor materials and the doping impurities introduced into the materials during manufacture.[7] These techniques are used to create special-purpose diodes that perform many different functions.[7] For example, diodes are used to regulate voltage (Zener diodes), to protect circuits from high voltage surges (avalanche diodes), to electronically tune radio and TV receivers (varactor diodes), to generate radio-frequency oscillations (tunnel diodes, Gunn diodes, IMPATT diodes), and to produce light (light-emitting diodes). Tunnel, Gunn and IMPATT diodes exhibit negative resistance, which is useful in microwave and switching circuits.

Diodes, both vacuum and semiconductor, can be used as shot-noise generators.

## 4.1.2 History

Thermionic (vacuum-tube) diodes and solid-state (semiconductor) diodes were developed separately, at approximately the same time, in the early 1900s, as radio receiver detectors.[8] Until the 1950s, vacuum diodes were used more frequently in radios because the early point-contact semiconductor diodes were less stable. In addition, most receiving sets had vacuum tubes for amplification that could easily have the thermionic diodes included in the tube (for example the 12SQ7 double diode triode), and vacuum-tube rectifiers and gas-filled rectifiers were capable of handling some high-voltage/high-current rectification tasks better than the semiconductor diodes (such as selenium rectifiers) that were available at that time.

## 4.1.3 Semiconductor diodes

### 4.1.3.1 Point-contact diodes

Point-contact diodes were developed starting in the 1930s, out of the early crystal detector technology, and are now generally used in the 3 to 30 gigahertz range. Point-

contact diodes use a small diameter metal wire in contact with a semiconductor crystal, and are of either non-welded contact type or welded contact type. Non-welded contact construction utilizes the Schottky barrier principle. The metal side is the pointed end of a small diameter wire that is in contact with the semiconductor crystal. In the welded contact type, a small P region is formed in the otherwise N type crystal around the metal point during manufacture by momentarily passing a relatively large current through the device. Point contact diodes generally exhibit lower capacitance, higher forward resistance and greater reverse leakage than junction diodes.

### 4.1.3.2 Junction diodes

#### 4.1.3.2.1 p–n junction diode

A p–n junction diode is made of a crystal of semiconductor, usually silicon, but germanium and gallium arsenide are also used. Impurities are added to it to create a region on one side that contains negative charge carriers (electrons), called an n-type semiconductor, and a region on the other side that contains positive charge carriers (holes), called a p-type semiconductor. When the n-type and p-type materials are attached together, a momentary flow of electrons occur from the n to the p side resulting in a third region between the two where no charge carriers are present. This region is called the depletion region because there are no charge carriers (neither electrons nor holes) in it. The diode's terminals are attached to the n-type and p-type regions. The boundary between these two regions, called a p–n junction, is where the action of the diode takes place. When a sufficiently higher electrical potential is applied to the P side (the anode) than to the N side (the cathode), it allows electrons to flow through the depletion region from the N-type side to the P-type side. The junction does not allow the flow of electrons in the opposite direction when the potential is applied in reverse, creating, in a sense, an electrical check valve.

#### 4.1.3.2.2 Schottky diode

Another type of junction diode, the Schottky diode, is formed from a metal–semiconductor junction rather than a p–n junction, which reduces capacitance and increases switching speed.

## 4.1.4 Current–voltage characteristic

A semiconductor diode's behavior in a circuit is given by its current–voltage characteristic, or I–V graph (see graph below). The shape of the curve is determined by the transport of charge carriers through the so-called depletion layer or depletion region that exists at the p–n junction between differing semiconductors. When a p–n junction is first created, conduction-band (mobile) electrons from the N-doped region diffuse into the P-dopedregion where there is a large population of holes (vacant places for electrons) with which the electrons "recombine". When a mobile electron recombines with a hole, both hole and electron vanish, leaving behind an immobile positively charged donor (dopant) on the N side and negatively charged acceptor (dopant) on the P side. The region around the p–n junction becomes depleted of charge carriers and thus behaves as an insulator.

However, the width of the depletion region (called the depletion width) cannot grow without limit. For each electron–hole pair recombination made, a positively charged dopant ion is left behind in the N-doped region, and a negatively charged dopant ion is created in the P-doped region. As recombination proceeds and more ions are created, an increasing electric field develops through the depletion zone that acts to slow and then finally stop recombination. At this point, there is a "built-in" potential across the depletion zone.

### 4.1.4.1 Reverse bias

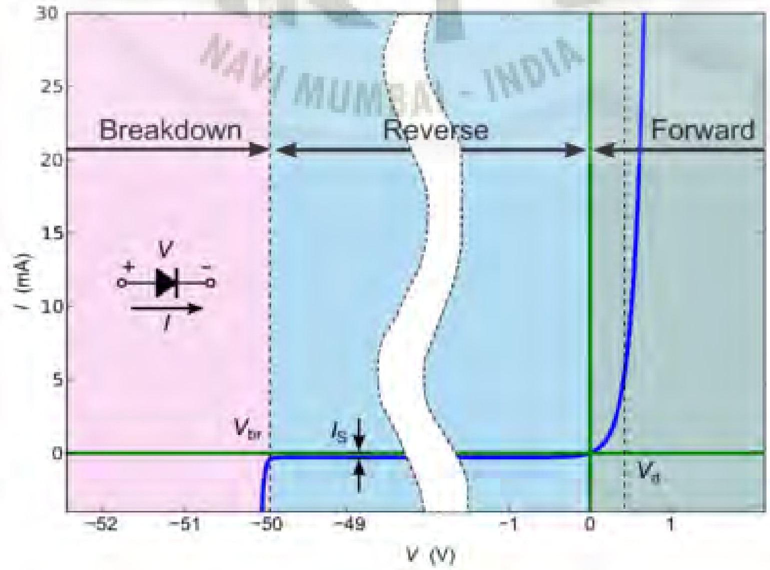
If an external voltage is placed across the diode with the same polarity as the built-in potential, the depletion zone continues to act as an insulator, preventing any significant electric current flow (unless electron–hole pairs are actively being created in the junction by, for instance, light; see photodiode). This is called the reverse bias phenomenon.

### 4.1.4.2 Forward bias

However, if the polarity of the external voltage opposes the built-in potential, recombination can once again proceed, resulting in a substantial electric current through the p–n junction (i.e. substantial numbers of electrons and holes recombine at the junction). For silicon diodes, the built-in potential is approximately 0.7 V (0.3 V for germanium and 0.2 V for Schottky). Thus, if an external voltage greater than and opposite to the built-in voltage is applied, a current will flow and the diode is said to be "turned on" as it has been given an external forward bias. The diode is commonly said to have a forward "threshold" voltage, above which it conducts and below which conduction stops. However, this is only an approximation as the forward characteristic is smooth (see I-V graph above).

A diode's I–V characteristic can be approximated by four regions of operation:

1. At very large reverse bias, beyond the peak inverse voltage or PIV, a process called reverse breakdown occurs that causes a large increase in current (i.e., a large number of electrons and holes are created at, and move away from the p–n junction) that usually damages the device permanently. The avalanche diode is deliberately designed for use in that manner. In the Zener diode, the concept of PIV is not applicable. A Zener diode contains a heavily doped p–n junction allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material, such that the reverse voltage is "clamped" to a known value (called the Zener voltage), and avalanche does not occur. Both devices, however, do have a limit to the maximum current and power they can withstand in the clamped reverse-voltage region. Also, following the end of forward conduction in any diode, there is reverse current for a short time. The device does not attain its full blocking capability until the reverse current ceases.
2. For a bias less than the PIV, the reverse current is very small. For a normal P–N rectifier diode, the reverse current through the device in the micro-ampere (µA) range is very low. However, this is temperature dependent, and at sufficiently high temperatures, a substantial amount of reverse current can be observed (mA or more). There is also a tiny surface leakage current caused by electrons simply going around the diode as though it were an imperfect insulator.
3. With a small forward bias, where only a small forward current is conducted, the current–voltage curve is exponential in accordance with the ideal diode equation. There is a definite forward voltage at which the diode starts to conduct significantly. This is called the knee voltage or cut-in voltage and is equal to the barrier potential of the p-n junction. This is a feature of the exponential curve, and appears sharper on a current scale more compressed than in the diagram shown here.
4. At larger forward currents the current-voltage curve starts to be dominated by the ohmic resistance of the bulk semiconductor. The curve is no longer exponential, it is asymptotic to a straight line whose slope is the bulk resistance. This region is particularly important for power diodes. The diode can be modeled as an ideal diode in series with a fixed resistor.



**I–V (current vs. voltage) characteristics of a p–n junction diode**

In a small silicon diode operating at its rated currents, the voltage drop is about 0.6 to 0.7 volts. The value is different for other diode types—Schottky diodescan be rated as low as 0.2 V, germanium diodes 0.25 to 0.3 V, and red or blue light-emitting diodes (LEDs) can have values of 1.4 V and 4.0 V respectively.[citation needed]

At higher currents the forward voltage drop of the diode increases. A drop of 1 V to 1.5 V is typical at full rated current for power diodes.

### 4.1.4.3 Shockley diode equation

The Shockley ideal diode equation or the diode law (named after the bipolar junction transistor co-inventor William Bradford Shockley) gives the I–V characteristic of an ideal diode in either forward or reverse bias (or no bias). The following equation is called the Shockley ideal diode equation when n, the ideality factor, is set equal to 1 :

$$I = I_S \left( e^{\frac{V_D}{nV_T}} - 1 \right)$$

where

$I$ is the diode current,

$I_S$ is the reverse bias saturation current (or scale current),

$V_D$ is the voltage across the diode,

$V_T$ is the thermal voltage, and

n is the ideality factor, also known as the quality factor or sometimes emission coefficient. The ideality factor n typically varies from 1 to 2 (though can in some cases be higher), depending on the fabrication process and semiconductor material and is set equal to 1 for the case of an "ideal" diode (thus the n is sometimes omitted). The ideality factor was added to account for imperfect junctions as observed in real transistors. The factor mainly accounts for carrier recombination as the charge carriers cross the depletion region.

The thermal voltage $V_T$ is approximately 25.85 mV at 300 K, a temperature close to "room temperature" commonly used in device simulation software. At any temperature it is a known constant defined by:

$$V_T = \frac{kT}{q},$$

where k is the Boltzmann constant, T is the absolute temperature of the p–n junction, and q is the magnitude of charge of an electron (the elementary charge).

The reverse saturation current, $I_S$, is not constant for a given device, but varies with temperature; usually more significantly than $V_T$, so that $V_D$ typically decreases as T increases.

The Shockley ideal diode equation or the diode law is derived with the assumption that the only processes giving rise to the current in the diode are drift (due to electrical field), diffusion, and thermal recombination–generation (R–G) (this equation is derived by setting n = 1 above). It also assumes that the R–G current in the depletion region is insignificant. This means that the Shockley ideal diode equation doesn't account for the processes involved in reverse breakdown and photon-assisted R–G. Additionally, it doesn't describe the "leveling off" of the I–V curve at high forward bias due to internal resistance. Introducing the ideality factor, n, accounts for recombination and generation of carriers.

Under reverse bias voltages the exponential in the diode equation is negligible, and the current is a constant (negative) reverse current value of $-I_S$. The reverse breakdown region is not modeled by the Shockley diode equation.

For even rather small forward bias voltages the exponential is very large, since the thermal voltage is very small in comparison. The subtracted '1' in the diode equation is then negligible and the forward diode current can be approximated by

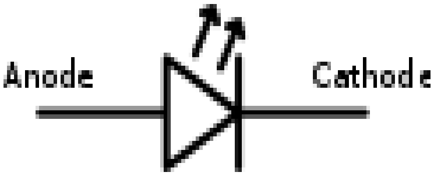
$$I = I_S e^{\frac{V_D}{n V_T}}$$

The use of the diode equation in circuit problems is illustrated in the article on diode modeling.

## 4.1.5 Types of semiconductor diode

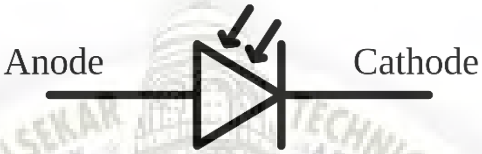
### Light-emitting diodes (LEDs)

In a diode formed from a direct band-gap semiconductor, such as gallium arsenide, charge carriers that cross the junction emit photons when they recombine with the majority carrier on the other side. Depending on the material, wavelengths (or colors)[39] from the infrared to the near ultraviolet may be produced.[40] The first LEDs were red and yellow, and higher-frequency diodes have been developed over time. All LEDs produce incoherent, narrow-spectrum light; "white" LEDs are actually a blue LED with a yellow scintillator coating, or combinations of three LEDs of a different color. LEDs can also be used as low-efficiency photodiodes in signal applications. An LED may be paired with a photodiode or phototransistor in the same package, to form an opto-isolator.



## Photodiodes

All semiconductors are subject to optical charge carrier generation. This is typically an undesired effect, so most semiconductors are packaged in light blocking material. Photodiodes are intended to sense light(photodetector), so they are packaged in materials that allow light to pass, and are usually PIN (the kind of diode most sensitive to light).[41] A photodiode can be used in solar cells, in photometry, or in optical communications. Multiple photodiodes may be packaged in a single device, either as a linear array or as a two-dimensional array. These arrays should not be confused with charge-coupled devices.

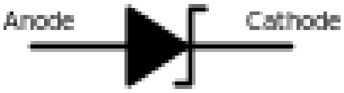


## Schottky diodes

Schottky diodes are constructed from a metal to semiconductor contact. They have a lower forward voltage drop than p–n junction diodes. Their forward voltage drop at forward currents of about 1 mA is in the range 0.15 V to 0.45 V, which makes them useful in voltage clamping applications and prevention of transistor saturation. They can also be used as low loss rectifiers, although their reverse leakage current is in general higher than that of other diodes. Schottky diodes are majority carrier devices and so do not suffer from minority carrier storage problems that slow down many other diodes—so they have a faster reverse recovery than p–n junction diodes.

## Zener diodes

These can be made to conduct in reverse bias (backward), and are correctly termed reverse breakdown diodes. This effect, called Zener breakdown, occurs at a precisely defined voltage, allowing the diode to be used as a precision voltage reference. The term Zener diode is colloquially applied to several types of breakdown diodes, but strictly speaking Zener diodes have a breakdown voltage of below 5 volts, whilst avalanche diodes are used for breakdown voltages above that value. In practical voltage reference circuits, Zener and switching diodes are connected in series and opposite directions to



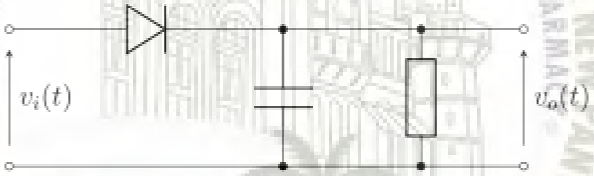
balance the temperature coefficient response of the diodes to near-zero. Some devices labeled as high-voltage Zener diodes are actually avalanche diodes (see above). Two (equivalent) Zeners in series and in reverse order, in the same package, constitute a transient absorber (or Transorb, a registered trademark).

## 4.1.6 Applications

### 4.1.6.1 Radio demodulation

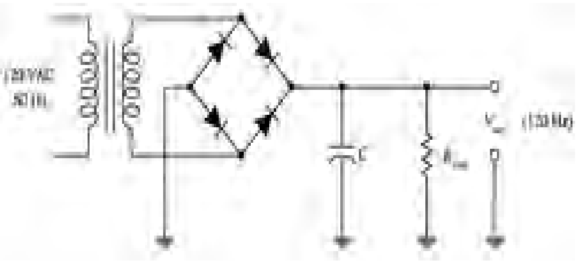
The first use for the diode was the demodulation of amplitude modulated (AM) radio broadcasts. The history of this discovery is treated in depth in the radio article. In summary, an AM signal consists of alternating positive and negative peaks of a radio carrier wave, whose amplitude or envelope is proportional to the original audio signal. The diode rectifies the AM radio frequency signal, leaving only the positive peaks of the carrier wave. The audio is then extracted from the rectified carrier wave using a simple filter and fed into an audio amplifier or transducer, which generates sound waves.

In microwave and millimeter wave technology, beginning in the 1930s, researchers improved and miniaturized the crystal detector. Point contact diodes (*crystal diodes*) and Schottky diodes are used in radar, microwave and millimeter wave detectors.



### 4.1.6.2 Power conversion

Rectifiers are constructed from diodes, where they are used to convert alternating current (ac) electricity into direct current (dc). Automotive alternators are a common example, where the diode, which rectifies the AC into dc, provides better performance than the commutator or earlier, dynamo. Similarly, diodes are also used in Cockcroft–Walton voltage multipliers to convert ac into higher ac voltages.



### 4.1.6.3 Over-voltage protection

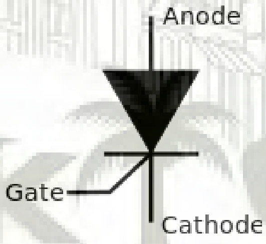
Diodes are frequently used to conduct damaging high voltages away from sensitive electronic devices. They are usually reverse-biased (non-conducting) under normal circumstances. When the voltage rises above the normal range, the diodes become forward-biased (conducting). For example, diodes are used in (stepper motor and H-bridge) motor controller and relay circuits to de-energize coils rapidly without the damaging voltage spikes that would otherwise occur. (A diode used in such an application is called a flyback diode). Many integrated circuits also incorporate diodes on the connection pins to prevent external voltages from damaging their sensitive transistors. Specialized diodes are used to protect from over-voltages at higher power (see Diode types above).

# 4.2 Silicon controlled rectifier

A **silicon controlled rectifier** or **semiconductor controlled rectifier** is a four-layer solid-state current-controlling device. The principle of four-layer p–n–p–n switching was developed by Moll, Tanenbaum, Goldey and Holonyak of Bell Laboratories in 1956. The practical demonstration of silicon controlled switching and detailed theoretical behavior of a device in agreement with the experimental results was presented by Dr Ian M. Mackintosh of Bell Laboratories in January 1958. The name "silicon controlled rectifier" is General Electric's trade name for a type of thyristor. The SCR was developed by a team of power engineers led by Gordon Hall[4]and commercialized by Frank W. "Bill" Gutzwiller in 1957.

Some sources define silicon-controlled rectifiers and thyristors as synonymous,[5] other sources define silicon-controlled rectifiers as a proper subset of the set of thyristors, those being devices with at least four layers of alternating n- and p-type material. According to Bill Gutzwiller, the terms "SCR" and "controlled rectifier" were earlier, and "thyristor" was applied later, as usage of the device spread internationally.

SCRs are unidirectional devices (i.e. can conduct current only in one direction) as opposed to TRIACs, which are bidirectional (i.e. current can flow through them in either direction). SCRs can be triggered normally only by currents going into the gate as opposed to TRIACs, which can be triggered normally by either a positive or a negative current applied to its gate electrode.



## 4.2.1 Modes of operation

There are three modes of operation for an SCR depending upon the biasing given to it:

1. Forward blocking mode (off state)
2. Forward conduction mode (on state)
3. Reverse blocking mode (off state)

### 4.2.1.1 Forward blocking mode

In this mode of operation, the anode (+) is given a positive voltage while the cathode (−) is given a negative voltage, keeping the gate at zero (0) potential i.e. disconnected. In this case junction J1 and J3 are forward-biased, while J2 is reverse-biased, due to which only a small leakage current exists from the anode to the cathode until the applied voltage reaches its breakover value, at which J2 undergoes avalanche breakdown, and at this breakover voltage it starts conducting, but below breakover voltage it offers very high resistance to the current and is said to be in the off state.

### 4.2.1.2 Forward conduction mode

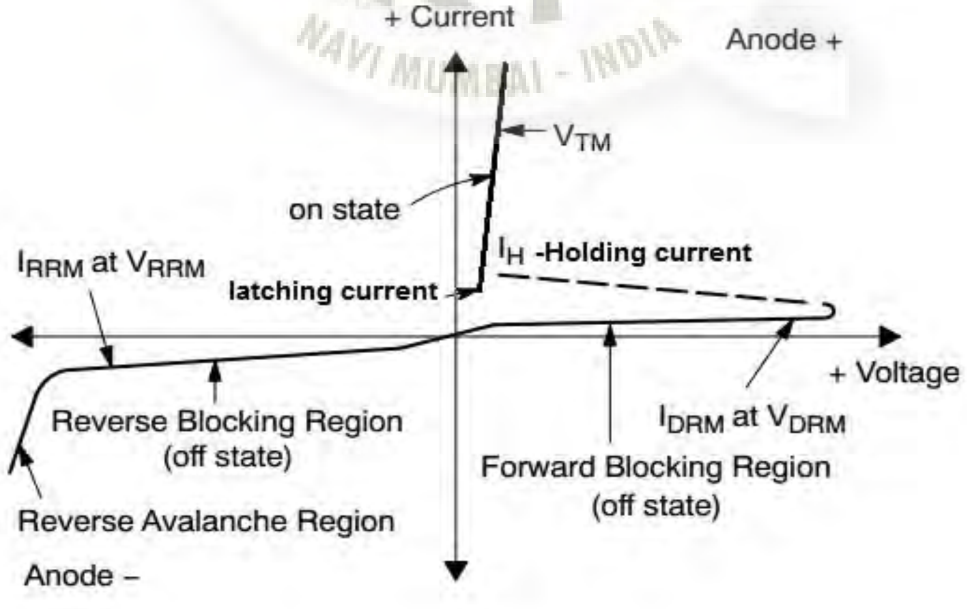
An SCR can be brought from blocking mode to conduction mode in two ways: Either by increasing the voltage between anode and cathode beyond the breakover voltage, or by applying a positive pulse at the gate. Once the SCR starts conducting, no more gate voltage is required to maintain it in the ON state.

There are two ways to turn it off:

1. Reduce the current through it below a minimum value called the holding current, or
2. With the gate turned off, short-circuit the anode and cathode momentarily with a push-button switch or transistor across the junction.
3.

### 4.2.1.3 Reverse blocking mode

When a negative voltage is applied to the anode and a positive voltage to the cathode, the SCR is in reverse blocking mode, making J1 and J3 reverse biased and J2 forward biased. The device behaves as two reverse-biassed diodes connected in series. A small leakage current flows. This is the reverse blocking mode. If the reverse voltage is increased, then at critical breakdown level, called the reverse breakdown voltage ($V_{BR}$), an avalanche occurs at J1 and J3 and the reverse current increases rapidly. SCRs are



available with reverse blocking capability, which adds to the forward voltage drop because of the need to have a long, low-doped P1 region. (If one cannot determine which region is P1, a labeled diagram of layers and junctions can help.)

Characteristic curve of a silicon-controlled rectifier

Usually, the reverse blocking voltage rating and forward blocking voltage rating are the same. The typical application for a reverse blocking SCR is in current-source inverters.

An SCR incapable of blocking reverse voltage is known as an asymmetrical SCR, abbreviated ASCR. It typically has a reverse breakdown rating in the tens of volts. ASCRs are used where either a reverse conducting diode is applied in parallel (for example, in voltage-source inverters) or where reverse voltage would never occur (for example, in switching power supplies or DC traction choppers).

Asymmetrical SCRs can be fabricated with a reverse conducting diode in the same package. These are known as RCTs, for reverse conducting thyristors.

## 4.2.2 Thyristor turn-on methods

1. forward-voltage triggering
2. gate triggering
3. dv/dt triggering
4. temperature triggering
5. light triggering

Forward-voltage triggering occurs when the anode–cathode forward voltage is increased with the gate circuit opened. This is known as avalanche breakdown, during which junction J2 will break down. At sufficient voltages, the thyristor changes to its on state with low voltage drop and large forward current. In this case, J1 and J3 are already forward-biased.

## 4.2.3 Applications

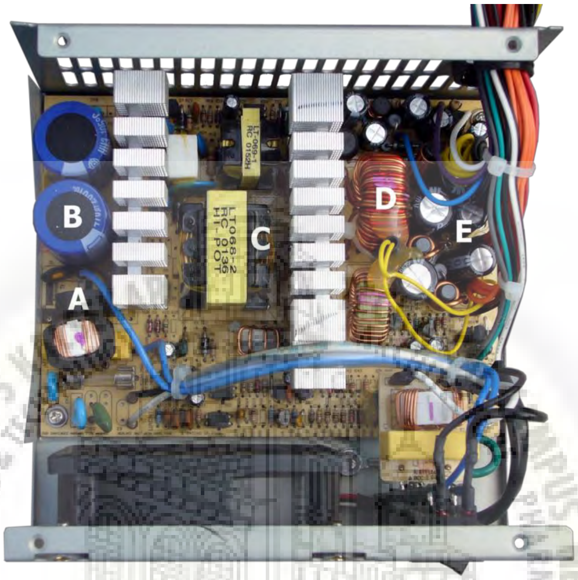
SCRs are mainly used in devices where the control of high power, possibly coupled with high voltage, is demanded. Their operation makes them suitable for use in medium- to high-voltage AC power control applications, such as lamp dimming, power regulators and motor control.

SCRs and similar devices are used for rectification of high-power AC in high-voltage dc power transmission. They are also used in the control of welding machines, mainly GTAW (gas tungsten arc welding) processes similar. It is used as switch in various devices.

# CHAPTER 5:- SMPS

# (SWITCHED MODE POWER SUPPLY)

## 5.1 INTODUCTION



A switched-mode power supply (switching-mode power supply, switch-mode power supply, switched power supply, SMPS, or switcher) is an electronic power supply that incorporates a switching regulator to convert electrical power efficiently. Like other power supplies, an SMPS transfers power from a DC or AC source (often mains power) to DC loads, such as a personal computer, while converting voltage and current characteristics. Unlike a linear power supply, the pass transistor of a switching-mode supply continually switches between low-dissipation, full-on and full-off states, and spends very little time in the high dissipation transitions, which minimizes wasted energy. Ideally, a switched-mode power supply dissipates no power. Voltage regulation is achieved by varying the ratio of on-to-off time. In contrast, a linear power supply regulates the output voltage by continually dissipating power in the pass transistor. This higher power conversion efficiency is an important advantage of a switched-mode power supply. Switched-mode power supplies may also be substantially smaller and lighter than a linear supply due to the smaller transformer size and weight.

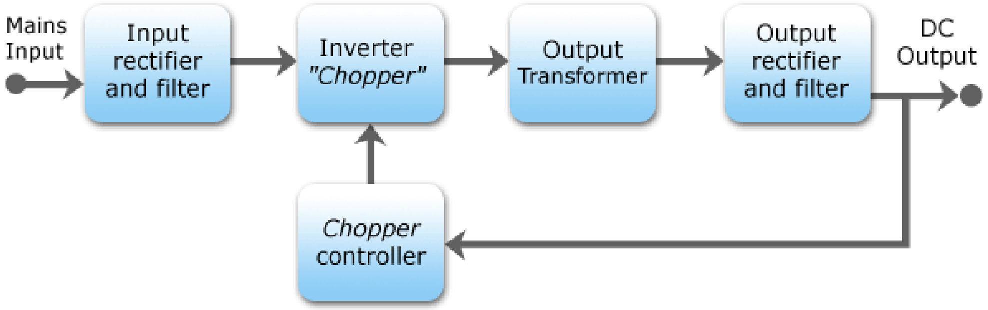
Switching regulators are used as replacements for linear regulators when higher efficiency, smaller size or lighter weight are required. They are, however, more complicated; their switching currents can cause electrical noise problems if not carefully suppressed, and simple designs may have a poor power factor.

### 5.1.1 Comparison of a linear power supply and a switched-mode power supply

| **Points** | **Linear power supply** | **Switching power supply** |
|---|---|---|
| Size and weight | Heatsinks for high power linear regulators add size and weight. Transformers, if used, are large due to low operating frequency (mains power frequency is at 50 or 60 Hz); otherwise can be compact due to low component count. | Smaller transformer (if used; else inductor) due to higher operating frequency (typically 50 kHz – 1 MHz). Size and weight of adequate RF shielding may be significant. |
| Output voltage | With transformer used, any voltages available; if transformerless, limited to what can be achieved with a voltage doubler. If unregulated, voltage varies significantly with load. | Any voltages available, limited only by transistor breakdown voltages in many circuits. Voltage varies little with load. |
| Efficiency, heat, and powerdissipation | If regulated: efficiency largely depends on voltage difference between input and output; output voltage is regulated by dissipating excess power as heat resulting in a typical efficiency of 30–40%.[18] If unregulated, transformer iron and copper losses may be the only significant sources of inefficiency. | Output is regulated using duty cyclecontrol; the transistors are switched fully on or fully off, so very little resistive losses between input and the load. The only heat generated is in the non-ideal aspects of the components and quiescent current in the control circuitry. |
| Complexity | Unregulated may be simply a diode and capacitor; regulated has a voltage-regulating circuit and a noise-filtering capacitor; usually a simpler circuit | Consists of a controller IC, one or several power transistors and diodes as well as a power transformer, inductors, and filter capacitors. Some |

| | | |
|---|---|---|
| | (and simpler feedback loop stability criteria) than switched-mode circuits. | design complexities present (reducing noise/interference; extra limitations on maximum ratings of transistors at high switching speeds) not found in linear regulator circuits. |
| Electronic noise at the output terminals | Unregulated PSUs may have a little AC ripple superimposed upon the DC component at twice mains frequency (100–120 Hz). It can cause audible mains hum in audio equipment, brightness ripples or banded distortions in analog security cameras. | Noisier due to the switching frequency of the SMPS. An unfiltered output may cause glitches in digital circuits or noise in audio circuits. |
| Power factor | Low for a regulated supply because current is drawn from the mains at the peaks of the voltage sinusoid, unless a choke-input or resistor-input circuit follows the rectifier (now rare). | Ranging from very low to medium since a simple SMPS without PFC draws current spikes at the peaks of the AC sinusoid. |
| Inrush current | Large current when mains-powered linear power supply equipment is switched on until magnetic flux of transformer stabilises and capacitors charge completely, unless a slow-start circuit is used. | Extremely large peak "in-rush" surge current limited only by the impedance of the input supply and any series resistance to the filter capacitors. |

## 5.1.2 Theory of operation

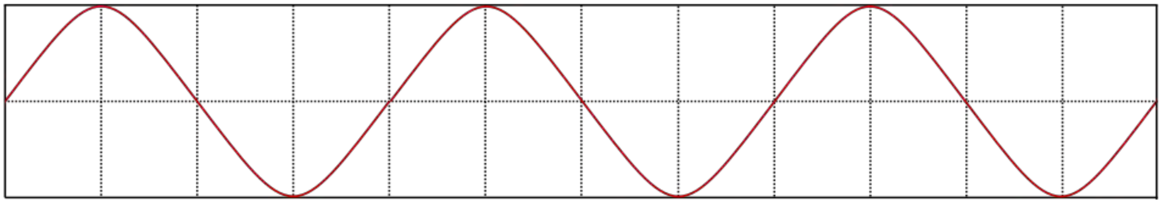


Block diagram of a mains operated AC/DC SMPS with output voltage regulation

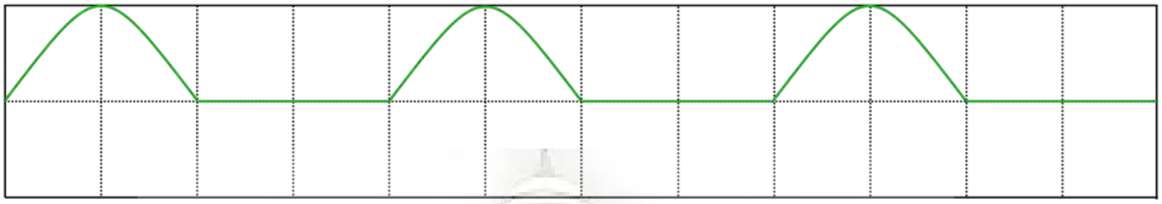
**Input rectifier stage**

If the SMPS has an AC input, then the first stage is to convert the input to DC. This is called *rectification*. An SMPS with a DC input does not require this stage. In some power supplies (mostly computer ATX power supplies), the rectifier circuit can be configured as a voltage doubler by the addition of a switch operated either manually or automatically. This feature permits operation from power sources that are normally at 115 V or at 230 V. The rectifier produces an unregulated DC voltage which is then sent to a large filter capacitor. The current drawn from the mains supply by this rectifier circuit occurs in short pulses around the AC voltage peaks. These pulses have significant high frequency energy which reduces the power factor. To correct for this, many newer SMPS will use a special PFC circuit to make the input current follow the sinusoidal shape of the AC input voltage, correcting the power factor. Power supplies that use active PFC usually are auto-ranging, supporting input voltages from ~100 VAC – 250 VAC, with no input voltage selector switch.

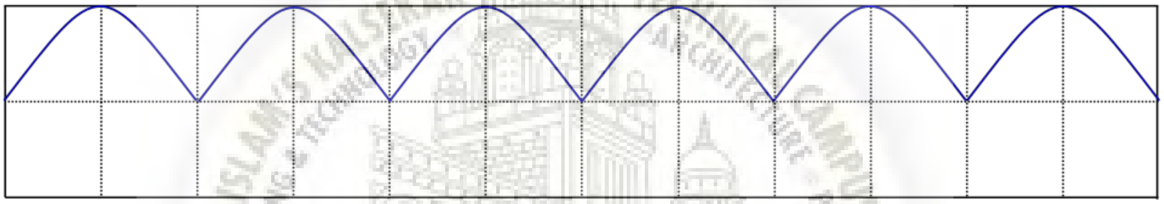
An SMPS designed for AC input can usually be run from a DC supply, because the DC would pass through the rectifier unchanged.[22] If the power supply is designed for 115 VAC and has no voltage selector switch, the required DC voltage would be 163 VDC (115 × √2). This type of use may be harmful to the rectifier stage, however, as it will only use half of diodes in the rectifier for the full load. This could possibly result in overheating of these components, causing them to fail prematurely. On the other hand, if the power supply has a voltage selector switch, based on the Delon circuit, for 115/230 V (computer ATX power supplies typically are in this category), the selector switch would have to be put in the 230 V position, and the required voltage would be 325 VDC (230 × √2). The diodes in this type of power supply will handle the DC current just fine because they are rated to handle double the nominal input current when operated in the 115 V mode, due to the operation of the voltage doubler. This is because the doubler, when in operation, uses only half of the bridge rectifier and runs twice as much current through it.



Sinusoidal Signal



Half-wave Rectification



Full-wave Rectification

AC, half-wave and full-wave rectified signals

### Inverter stage

The inverter stage converts DC, whether directly from the input or from the rectifier stage described above, to AC by running it through a power oscillator, whose output transformer is very small with few windings at a frequency of tens or hundreds of kilohertz. The frequency is usually chosen to be above 20 kHz, to make it inaudible to humans. The switching is implemented as a multistage (to achieve high gain) MOSFET amplifier. MOSFETs are a type of transistor with a low on-resistance and a high current-handling capacity.

### Voltage converter and output rectifier

If the output is required to be isolated from the input, as is usually the case in mains power supplies, the inverted AC is used to drive the primary winding of a high-frequency transformer. This converts the voltage up or down to the required output level on its secondary winding. The output transformer in the block diagram serves this purpose.

If a **DC** output is required, the **AC** output from the transformer is rectified. For output voltages above ten volts or so, ordinary silicon diodes are commonly used. For lower voltages, Schottky diodes are commonly used as the rectifier elements; they have the advantages of faster recovery times than silicon diodes (allowing low-loss operation at higher frequencies) and a lower voltage drop when conducting. For even lower output voltages, MOSFETs may be used as synchronous rectifiers; compared to Schottky diodes, these have even lower conducting state voltage drops.

The rectified output is then smoothed by a filter consisting of inductors and capacitors. For higher switching frequencies, components with lower capacitance and inductance are needed.

Simpler, non-isolated power supplies contain an inductor instead of a transformer. This type includes *boost converters*, *buck converters*, and the *buck–boost converters*. These belong to the simplest class of single input, single output converters which use one inductor and one active switch. The buck converter reduces the input voltage in direct proportion to the ratio of conductive time to the total switching period, called the duty cycle. For example an ideal buck converter with a 10 V input operating at a 50% duty cycle will produce an average output voltage of 5 V. A feedback control loop is employed to regulate the output voltage by varying the duty cycle to compensate for variations in input voltage. The output voltage of a boost converter is always greater than the input voltage and the buck–boost output voltage is inverted but can be greater than, equal to, or less than the magnitude of its input voltage. There are many variations and extensions to this class of converters but these three form the basis of almost all isolated and non-isolated DC to DC converters. By adding a second inductor the Ćuk and SEPIC converters can be implemented, or, by adding additional active switches, various bridge converters can be realized.

Other types of SMPSs use a capacitor–diode voltage multiplier instead of inductors and transformers. These are mostly used for generating high voltages at low currents (*Cockcroft-Walton generator*). The low voltage variant is called charge pump.

Regulation

A feedback circuit monitors the output voltage and compares it with a reference voltage, as shown in the block diagram above. Depending on design and safety requirements, the controller may contain an isolation mechanism (such as an opto-coupler) to isolate it from the DC output. Switching supplies in computers, TVs and VCRs have these opto-couplers to tightly control the output voltage.

*Open-loop regulators* do not have a feedback circuit. Instead, they rely on feeding a constant voltage to the input of the transformer or inductor, and assume that the output will be correct. Regulated designs compensate for the impedance of the transformer or coil. Monopolar designs also compensate for the magnetic hysteresis of the core.

The feedback circuit needs power to run before it can generate power, so an additional non-switching power-supply for stand-by is added.

**Advantages and disadvantages**

The main advantage of the switching power supply is greater efficiency than linear regulators because the switching transistor dissipates little power when acting as a switch.

Other advantages include smaller size and lighter weight from the elimination of heavy line-frequency transformers, and comparable heat generation. Standby power loss is often much less than transformers.

Disadvantages include greater complexity, the generation of high-amplitude, high-frequency energy that the low-pass filter must block to avoid electromagnetic interference (EMI), a ripple voltage at the switching frequency and the harmonic frequencies thereof.

Very low cost SMPSs may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non-power-factor-corrected SMPSs also cause harmonic distortion.

# 5.2 TRANFORMER DESIGN

Any switched-mode power supply that gets its power from an AC power line (called an "off-line" converter requires a transformer for galvanic isolation. Some DC-to-DC converters may also include a transformer, although isolation may not be critical in these cases. SMPS transformers run at high frequency. Most of the cost savings (and space savings) in off-line power supplies result from the smaller size of the high frequency transformer compared to the 50/60 Hz transformers formerly used. There are additional design tradeoffs.

The terminal voltage of a transformer is proportional to the product of the core area, magnetic flux, and frequency. By using a much higher frequency, the core area (and so the mass of the core) can be greatly reduced. However, core losses increase at higher frequencies. Cores generally use ferrite material which has a low loss at the high frequencies and high flux densities used. The laminated iron cores of lower-frequency (<400 Hz) transformers would be unacceptably lossy at switching frequencies of a few kilohertz. Also, more energy is lost during transitions of the switching semiconductor at higher frequencies. Furthermore, more attention to the physical layout of the circuit board is required as parasitics become more significant, and the amount of electromagnetic interference will be more pronounced.

## 5.2.1 Copper loss

At low frequencies (such as the line frequency of 50 or 60 Hz), designers can usually ignore the skin effect. For these frequencies, the skin effect is only significant when the conductors are large, more than 0.3 inches (7.6 mm) in diameter.

Switching power supplies must pay more attention to the skin effect because it is a source of power loss. At 500 kHz, the skin depth in copper is about 0.003 inches (0.076 mm) – a dimension smaller than the typical wires used in a power supply. The effective resistance of conductors increases, because current concentrates near the surface of the conductor and the inner portion carries less current than at low frequencies.

The skin effect is exacerbated by the harmonics present in the high speed PWM switching waveforms. The appropriate skin depth is not just the depth at the fundamental, but also the skin depths at the harmonics.[25]

In addition to the skin effect, there is also a proximity effect, which is another source of power loss.

## 5.2.2 Power factor

Simple off-line switched mode power supplies incorporate a simple full-wave rectifier connected to a large energy storing capacitor. Such SMPSs draw current from the AC line in short pulses when the mains instantaneous voltage exceeds the voltage across this capacitor. During the remaining portion of the AC cycle the capacitor provides energy to the power supply.

As a result, the input current of such basic switched mode power supplies has high harmonic content and relatively low power factor. This creates extra load on utility lines, increases heating of building wiring, the utility transformers, and standard AC electric motors, and may cause stability problems in some applications such as in emergency generator systems or aircraft generators. Harmonics can be removed by filtering, but the filters are expensive. Unlike displacement power factor created by linear inductive or capacitive loads, this distortion cannot be corrected by addition of a single linear component. Additional circuits are required to counteract the effect of the brief current pulses. Putting a current regulated boost chopper stage after the off-line rectifier (to charge the storage capacitor) can correct the power factor, but increases the complexity and cost.

In 2001, the European Union put into effect the standard IEC/EN61000-3-2 to set limits on the harmonics of the AC input current up to the 40th harmonic for equipment above 75 W. The standard defines four classes of equipment depending on its type and current waveform. The most rigorous limits (class D) are established for personal computers, computer monitors, and TV receivers. To comply with these requirements, modern switched-mode power supplies normally include an additional power factor correction (PFC) stage.

### 5.2.3 Efficiency and EMI

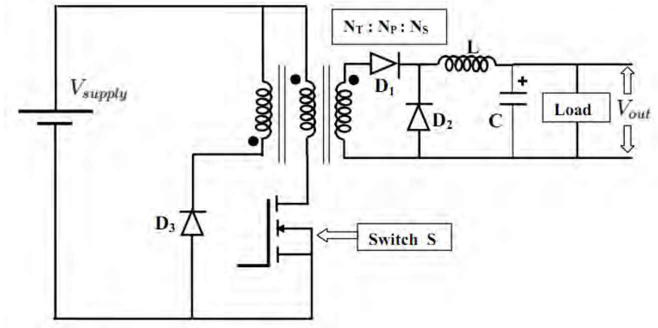
Higher input voltage and synchronous rectification mode makes the conversion process more efficient. The power consumption of the controller also has to be taken into account. Higher switching frequency allows component sizes to be shrunk, but can produce more RFI. A resonant forward converter produces the lowest EMI of any SMPS approach because it uses a soft-switching resonant waveform compared with conventional hard switching.

## 5.3 DIFFERENT TYPES OF SMPS

The different types of SMPS include the following

- Forward Converter
- Flyback Converter

### 5.3.1 Forward converter



The **forward converter** is a DC/DC converter that uses a transformer to increase or decrease the output voltage (depending on the transformer ratio) and provide galvanic isolation for the load. With multiple output windings, it is possible to provide both higher and lower voltage outputs simultaneously.

While it looks superficially like a flyback converter, it operates in a fundamentally different way, and is generally more energy efficient. A flyback converter stores energy in the magnetic field in the inductor air gap during the time the converter switching element (transistor) is conducting. When the switch turns off, the stored magnetic field collapses and the energy is transferred to the output of the flyback converter as electric current. The flyback converter can be viewed as two inductors sharing a common core with opposite polarity windings.

In contrast, the forward converter (which is based on a transformer with same-polarity windings, higher magnetizing inductance, and no air gap) does not store energy during the conduction time of the switching element — transformers cannot store a significant amount of energy, unlike inductors.[1] Instead, energy is passed directly to the output of the forward converter by transformer action during the switch conduction phase.

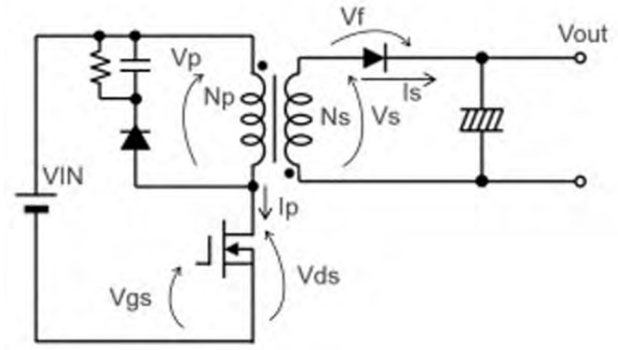
While the output voltage of a flyback converter is theoretically infinite, the maximum output voltage

The forward converter is typically used in off-line supplies to provide an intermediate power output level of 100–200 watts.

## Principle of Operation

The circuit of Fig. is basically a dc-to-dc buck converter with the addition of a transformer for output voltage isolation and scaling. When switch ‘S’ is turned on, input dc gets applied to the primary winding and simultaneously a scaled voltage appears across the transformer secondary. Dotted sides of both the windings are now having positive polarity. Diode ‘D1’, connected in series with the secondary winding gets forward biased and the scaled input voltage is applied to the low pass filter circuit preceding the load. The primary winding current enters through its dotted end while the secondary current comes out of the dotted side and their magnitudes are inversely proportional to their turns-ratio. Thus, as per the assumption of an ideal transformer, the net magnetizing ampere-turns of the transformer is zero and there is no energy stored in the transformer core. When switch ‘S’ is turned off, the primary as well as the secondary winding currents are suddenly brought down to zero. Current through the filter inductor and the load continues without any abrupt change. Diode ‘D2’ provides the freewheeling path for this current. The required emf to maintain continuity in filter-inductor current and to maintain the forward bias voltage across D2 comes from the filter inductor ‘L’ itself. During freewheeling the filter inductor current will be decaying as it flows against the output voltage (Vop), but the presence of relatively large filter capacitor ‘C’ still maintains the output voltage nearly constant. The ripple in the output voltage must be within the acceptable limits. The supply switching frequency is generally kept sufficiently high such that the next turn-on of the switch takes place before the filter inductor current decays significantly. Needless to say, that the magnitudes of filter inductor and capacitor are to be chosen appropriately. The idea behind keeping filter inductor current nearly constant is to relieve the output capacitor from supplying large ripple current. [As per the circuit topology of Fig., the inductor and the capacitor together share the load-current drawn from the output. Under steady state condition, mean dc current supplied by the capacitor is zero but capacitor still supplies ripple current. For maintaining constant load current, the inductor and capacitor currentripples must be equal in magnitude but opposite in sense. Capacitors with higher ripple current rating are required to have much less equivalent series resistor (ESR) and equivalent series inductor (ESL) and as such they are bulkier and costlier. Also, the ESR and ESL of a practical capacitor causes ripple in its dc output voltage due to flow of ripple current through these series impedances. Since the output voltage is drawn from capacitor terminal the ripple in output voltage will be less if the capacitor is made to carry less ripple current.] For better understanding of the steady-state behavior of the converter, the circuit's operation is divided in two different modes, mode-1 and mode-2. Mode-1 corresponds to the 'on' duration of the switch and mode-2 corresponds to its 'off' duration. The following simplifying assumptions are made before proceeding to the detailed modewise analysis of the circuit: • ON state voltage drops of switches and diodes are neglected. Similarly, leakage currents through the off state devices is assumed zero. The switching-on and switching-off times of the switch and diodes are neglected. Version 2 EE IIT, Kharagpur 4 • The transformer used in the circuit is assumed to be ideal requiring no magnetizing current, having no leakage inductance and no losses. • The filter circuit elements like, inductors and capacitors are assumed loss-less. • For the simplified steady-state analysis of the circuit the switch duty ratio (δ), as defined in the previous chapters is assumed constant. • The input and output dc voltages are assumed to be constant and ripple-free. Current through the filter inductor (L) is assumed to be continuous.

## 5.3.2 Flyback Converter



**Introduction**

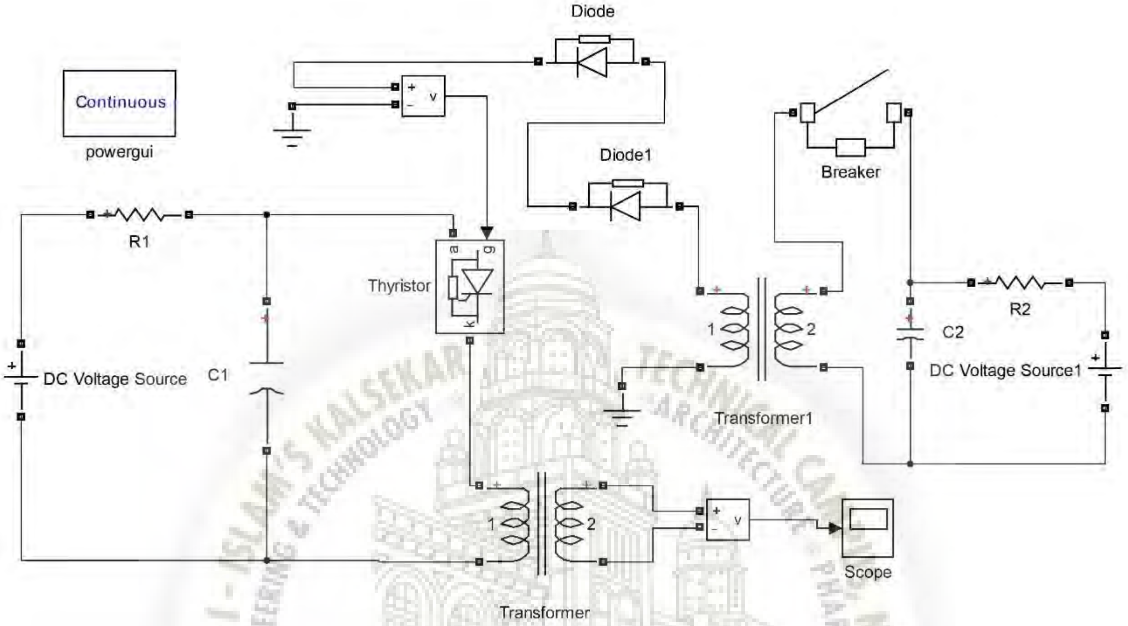
Fly-back converter is the most commonly used SMPS circuit for low output power applications where the output voltage needs to be isolated from the input main supply. The output power of fly-back type SMPS circuits may vary from few watts to less than 100 watts. The overall circuit topology of this converter is considerably simpler than other SMPS circuits. Input to the circuit is generally unregulated dc voltage obtained by rectifying the utility ac voltage followed by a simple capacitor filter. The circuit can offer single or multiple isolated output voltages and can operate over wide range of input voltage variation. In respect of energy-efficiency, fly-back power supplies are inferior to many other SMPS circuits but its simple topology and low cost makes it popular in low output power range. The commonly used fly-back converter requires a single controllable switch like, MOSFET and the usual switching frequency is in the range of 100 kHz. A twoswitch topology exists that offers better energy efficiency and less voltage stress across the switches but costs more and the circuit complexity also increases slightly. The present lesson is limited to the study of fly-back circuit of single switch topology.

## Principle of Operation

During its operation fly-back converter assumes different circuit-configurations. Each of these circuit configurations have been referred here as modes of circuit operation. The complete operation of the power supply circuit is explained with the help of functionally equivalent circuits in these different modes. As may be seen from the circuit diagram of Fig, when switch ‘S’ is on, the primary winding of the transformer gets connected to the input supply with its dotted end connected to the positive side. At this time the diode ‘D’ connected in series with the secondary winding gets reverse biased due to the induced voltage in the secondary (dotted end potential being higher). Thus with the turning on of switch ‘S’, primary winding is able to carry current but current in the secondary winding is blocked due to the reverse biased diode. The flux established in the transformer core and linking the windings is entirely due to the primary winding current. This mode of circuit has been described here as Mode-1 of circuit operation. Fig. shows (in bold line) the current carrying part of the circuit and Fig shows the circuit that is functionally equivalent to the fly-back circuit during mode-1. In the equivalent circuit shown, the conducting switch or diode is taken as a shorted switch and the device that is not conducting is taken as an open switch. This representation of switch is in line with our assumption where the switches and diodes are assumed to have ideal nature, having zero voltage drop during conduction and zero leakage current during off state.

# CHAPTER 6 : CIRCUIT ANALYSIS

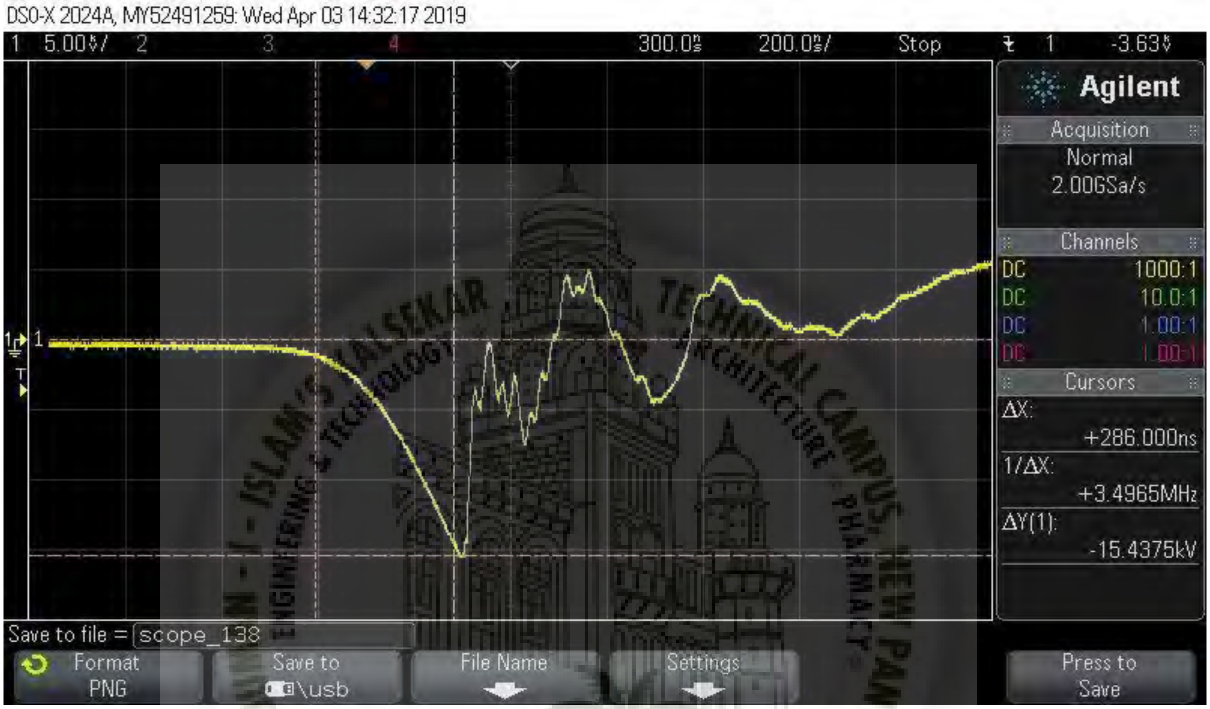
## TOPOLOGY 1



Circuit Diagram is shown in figure in this figure during the operation we are using three transformers one is toroidal transformer which is not shown in circuit diagram another is pulse transformer with ratio of (1:100) shown in circuit diagram as transformer and third transformer is isolation transformer with ratio of (1:1) shown in circuit diagram as transformer 1. in this circuit we are using two charging resistor R1 and R2 value of R1 is 10 MOHM and value of R2 is 10 KOHM . in this we are using two capacitor C1 and C2 value of C1 is 0.22 microfarad and value of C2 is 4.7 microfarad in this circuit we are using SCR for switching in this circuit we are also use two diodes as diode and diode1 shown in figure .in this circuit diagram we are also use a switch shown in figure as breaker

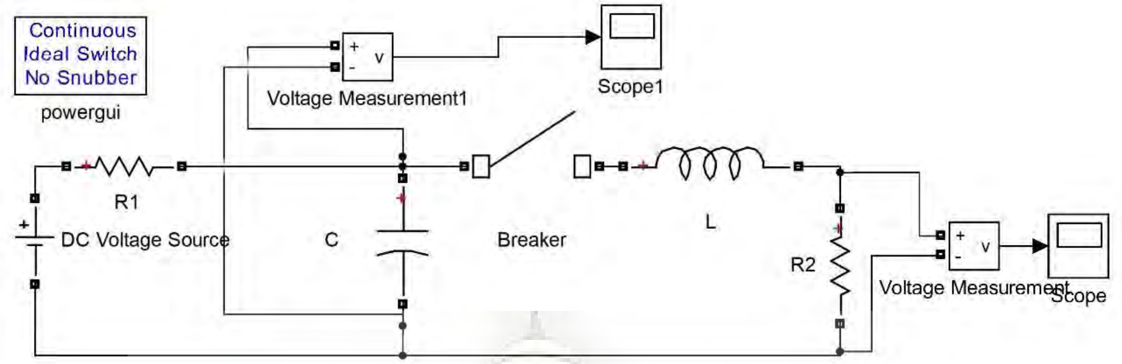
Now first discuss about source in this we are using 230 V 50 Hz supply given to the toroidal transformer toroidal transformer having one primary winding and two secondary winding in this two secondary winding one winding step up the voltage to rms 300-400 V and another winding step down the voltage to rms 12 V . output of toroidal transformer is given to the full wave bridge rectifier for converting AC to DC in this we are using two rectifiers.

Now we can consider circuit in two part one is main part and another is triggering part So output of the rectifier is given to the circuit ( both the part ) output of one rectifier 600 V peak is given to the capacitor C1 through charging resistor R1 after charging of capacitor C1 SCR is trigger with help of triggering circuit SCR connected in series with the pulse transformer the ratio of transformer is (1:100) so we get the output of the transformer 15.4 K voltage with the rise time of 286 nsec losses in transformer is high because frequency is very high . the waveform of the operation is shown below in figure



Voltage across transformer

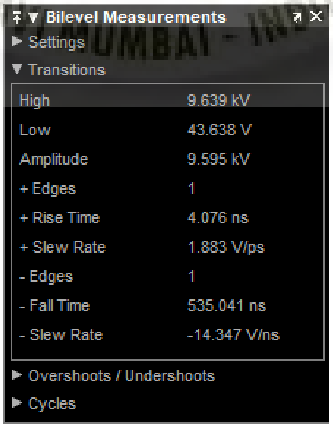
# TOPOLOGY 2 :



This topology is most important as rise time point of view we get rise time less than 10 nsec from the output of the circuit in this circuit we are not use any semiconductor switch in this circuit we are using breaker in this circuit we are using resistor R1 and R2 the value of R1 is 10 Mohm and the value of R2 50 in this circuit we are using capacitor C and inductor L .

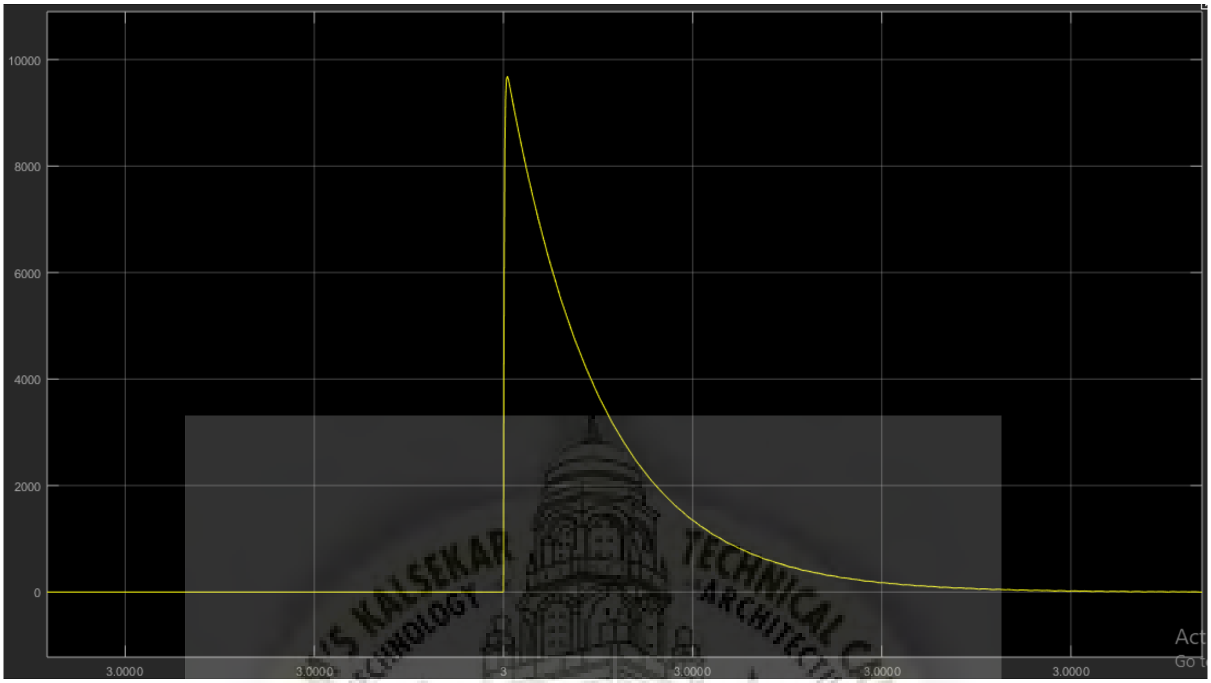
In this circuit we are using SMPS at supply side we get the output of SMPS 10 KV and this 10 KV we apply to circuit capacitor charge at 10 KV through charging resistor R1 after charging capacitor breaker is closed after 3 sec and the capacitor is discharge to the resistor R2 the voltage across the resistor is 9.639 KV and rise time is 4 nsec

The voltage across the resistor and the voltage across the capacitor shown in figure

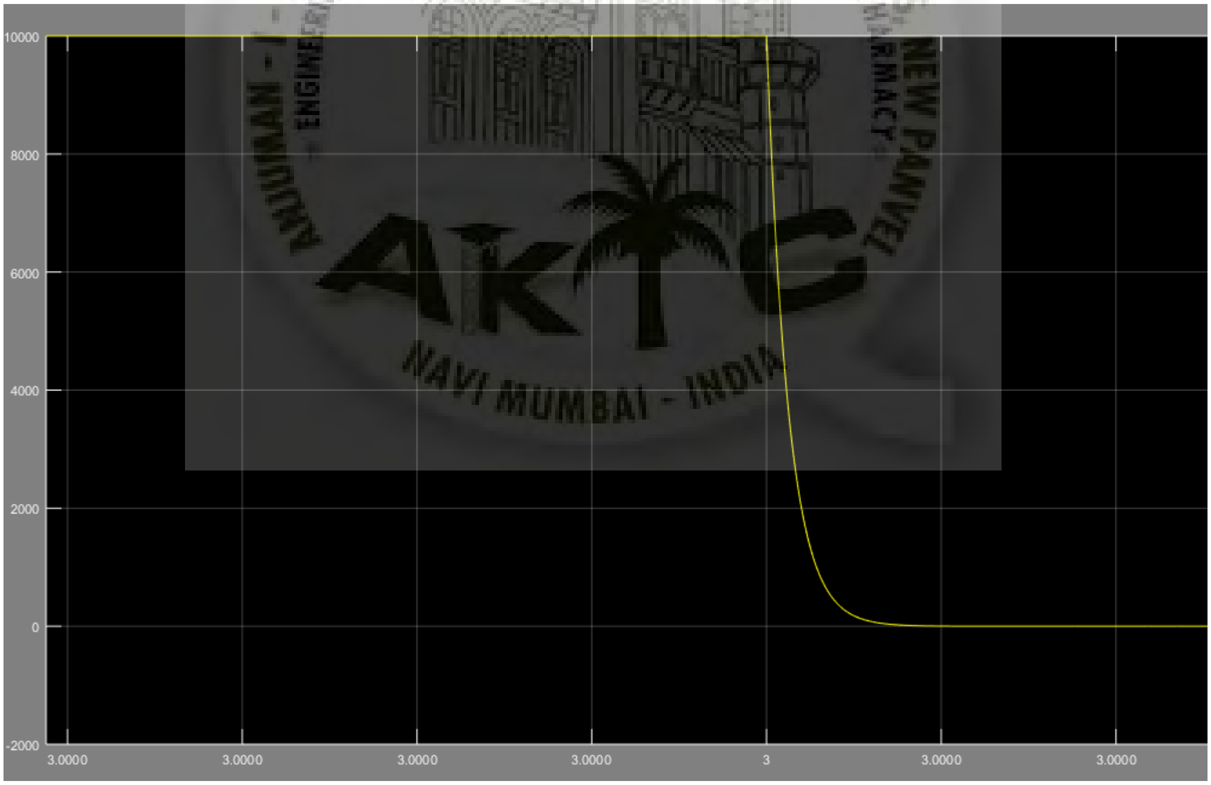


```
Bilevel Measurements
▶ Settings
▼ Transitions
High            9.639 kV
Low             43.638 V
Amplitude       9.595 kV
+ Edges         1
+ Rise Time     4.076 ns
+ Slew Rate     1.883 V/ps
- Edges         1
- Fall Time     535.041 ns
- Slew Rate     -14.347 V/ns
▶ Overshoots / Undershoots
▶ Cycles
```

In the bilevel measurements we can see the rise time is 4.076 nsec and voltage is 9.639 KV



voltage across resistor R2



voltage across capacitor C

we can see from waveform in this after closing switch at 3 sec capacitor is discharge shown in waveform

# CHAPTER 7 : CONCLUSION

In This Development of High Voltage Pulse Generator Module we have studied how to generate high voltage pulses.In this we have studied two topology topology 1 and topology 2 in the topology 1 with the help of pulse transformer in this we get the rise time less than 350 nsec also we generate high voltage 15 KV in this we studied the operation of transformer also we studied the operation of semiconductor switch SCR in the topology 2 we get the output voltage 9.6 KV and the rise time is less than 10 nsec .

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