Free eBOOK

Basic Electricity For Seafarers

Includes Relevant Topics for IMO Model Courses 7.02, 7.04 and 7.08

Elstan A. Fernandez | Divyam Verma | Krishnakumar| Jatin Manghani
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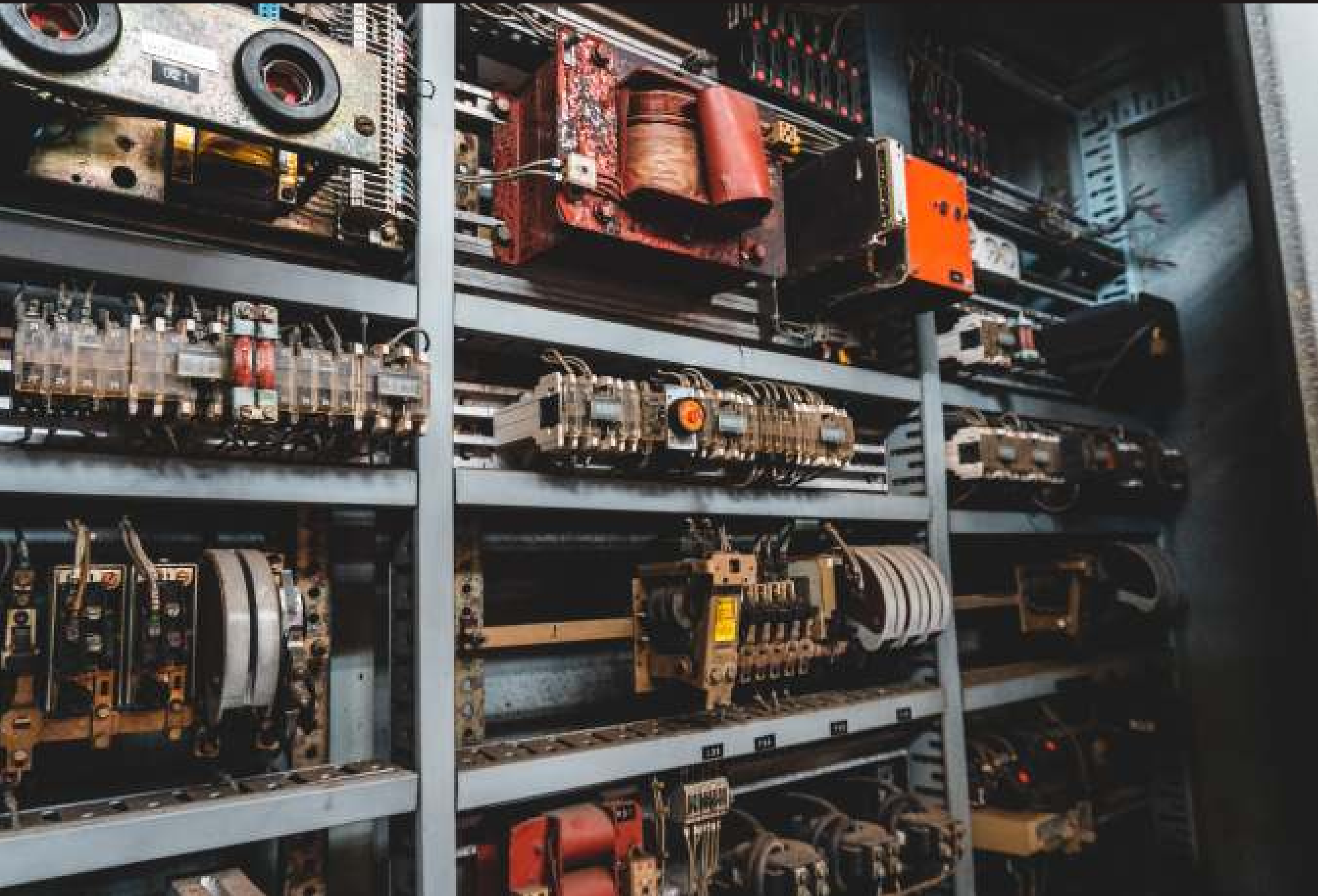

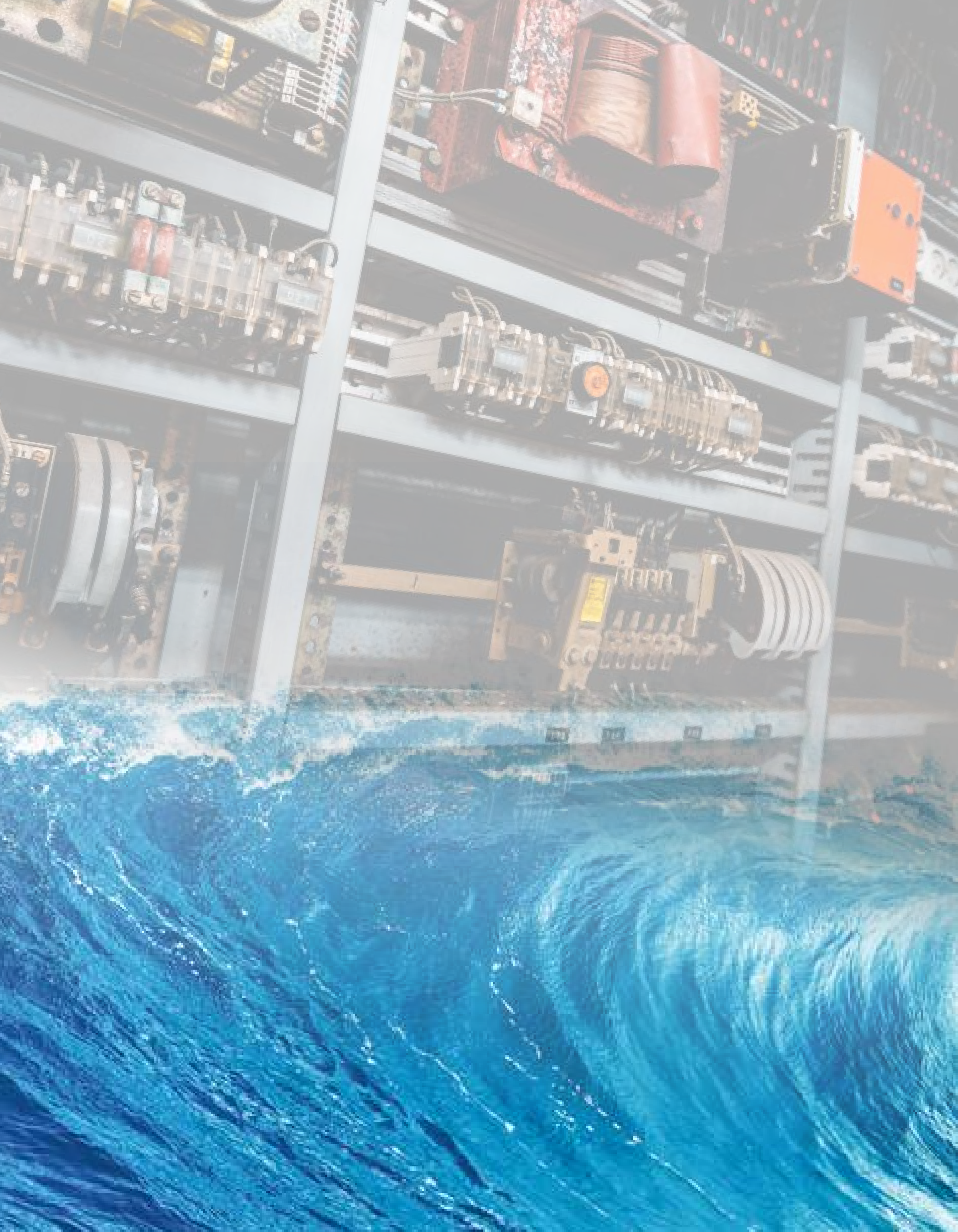

Basic Electricity for Seafarers

A Free Compilation

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And Electro Technical Officer Cadets

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Preface

No matter where we go or what we do in this world today, Electricity plays a pivotal role in day-to-day operations and in our life as well. It is befitting to note that at the very beginning of the vast syllabus for the IMO Model Courses 7.02 and 7.04 for Engineers at the Management and Operational Levels and also 7.08 for ETOs, great stress has been laid on the knowledge and understanding of Basic Elecrticity.

This little book has been compiled from various sources and hence is not for commercial benefits but purely to help those who are interested to learn the subject. It thus aims at helping engineers to recap their fundamentals and also apply the same in their work lives at sea and on land.

Acknowledgements

This book has been compiled from various resources, without which, it would not have been possible. The following are the sources of our informations to whom we are grateful and sure that our readers would be grateful too!

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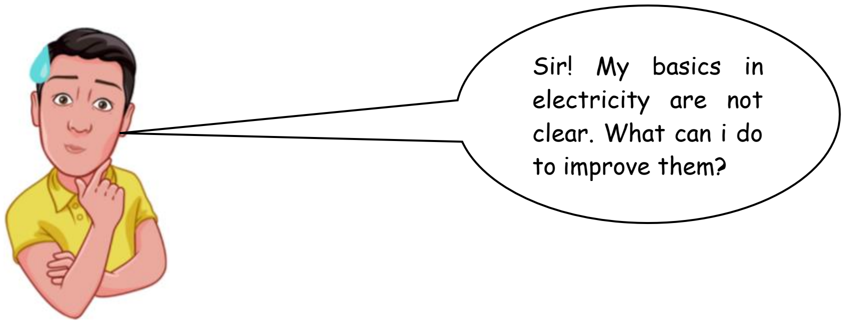
To Our Fellow Seafarers

and Would Be Seafarers Too

Chapter 1
Basic Laws in Electrical Theory



Chapter 1

1.1 The Origin of Ohm's Law

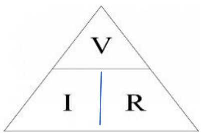
Ohm's law defines the relationship between voltage, resistance and current. This law is widely employed while designing electronic circuits. The electric current that runs the fans and kettles in our homes is guided by Ohm's law, a fundamental rule of electric current flow that was given by Georg Simon Ohm in the year 1827. The wide applicability of this law can be understood by the fact that despite being formulated almost 200 years ago, it still holds true today, and has relevance for almost all of us in our day-to-day lives.

Whether you are powering up your room heater or setting your iron to the cotton setting, Ohm's law is what makes it possible for you to achieve the desired flow of current for your precise needs. In the world of physics, this law is considered a significant and important way to determine the amount of electric current that flows through a conductor.

1.2 Definition of Ohm's Law

It states that under constant temperature and physical conditions, the amount of electric current (I) through a metal conductor in a circuit is directly proportional to the voltage (V) applied.

Ohm expressed this discovery in the form of a simple equation, describing how voltage, current, and resistance are interrelated:



$$V \propto I$$

$$V = I*R$$

$$I = \frac{V}{R} \quad or \quad R = \frac{V}{I}$$

Here, V = Voltage (volts), I = Current (amperes) and R = Resistance (Ohm)

This law can be easily understood with the analogy of observing the flow of water through a pipe. More water will come out of the pipe when more water pressure is applied. If the pipe's diameter is small, it will difficult for the water to flow, as compared to a pipe with a large diameter.

Similarly, at a given resistance value, when more voltage is applied across a conductor, more current will flow. If the resistance is low, the current will be high. Ohm's law also means that, if we know the values of any two quantities from voltage, current, or resistance in a circuit, we can determine the third.

1.3 Facts

The application of Ohm's law (based on V = IR) is limited to circuits with direct current (DC) only and does not work when there is an alternating current (AC) flowing through the circuit.

This law is also associated with the design and functioning of contemporary electronic devices, such as smartphones, laptops, and chargers which run on DC. It allows engineers to calculate an adequate supply of power through these devices.

The unit of resistance is named the Ohm (Ω), after Georg Simon Ohm, to honor his contributions to the field of physics.

This popular law of physics is said to be first discovered by English physicist Henry Cavendish who never published his scientific findings on electric current. Later on, when Ohm did his own research on the relation between voltage and current, he came across similar discoveries and published the law under his name.

A DC ammeter that is used to measure the direct current value across any DC device, also follows this law. Fuses and resistors that hinder the flow of electric current and serve as safety components in electronic appliances, function in accordance with the formulae mentioned in Ohm's law.

1.4 Kirchhoff's Laws

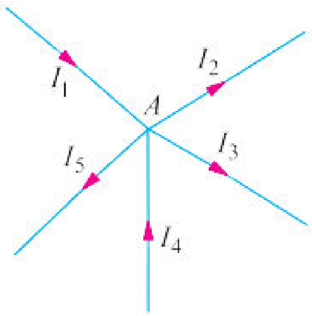
1.4.1 Kirchhoff's Current Law (KCL) or Point Law

It states that in any electrical network, the algebraic sum of the currents meeting at a point (or junction) is zero.

In other words, the total current leaving a junction equals the total current entering it.

Consider the example of a few conductors that come together at point A. Some conductors have currents that lead to point A, whereas others have currents that lead away from point A.

Assuming that the entering currents are positive and the emitted currents are negative, we obtain



$I_1 + (-I_2) + (-I_3) + (+ I_4) + (-I_5) = 0$

Or

$I_1 + I_4 - I_2 - I_3 - I_5 = 0$ or $I_1 + I_4 = I_2 + I_3 + I_5$

Or

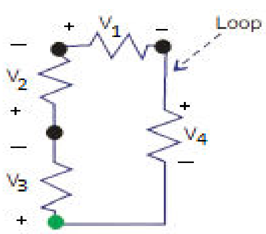
Sum of the Incoming currents = Sum of the Outgoing currents

The preceding conclusion may be expressed as $\sum I = 0$.

1.4.2 Kirchhoff's Voltage Law (KVL) or Kirchhoff's Second Law

It states that "in any closed loop network, the total voltage around the loop is equal to the sum of all the voltage drops within the same loop" which is also equal to zero.

In other words, the algebraic sum of all voltages within the loop must be equal to zero. Thus,



The Sum of the Voltages (Anti Clockwise)

$V_1 + V_2 + V_3 + V_4 = 0$

The Sum of the Voltages (Clockwise)

$-V_1 - V_4 - V_3 - V_2 = 0$

The basis for this rule is that if we start at a certain junction and circle the mesh before we return to the starting point, we must be at the same potential as when we began. As a result, all e.m.f. sources encountered along the way must be proportional to the voltage decreases in the system. Each voltage is given its proper symbol, plus or minus, the resistances.

1.5 Current Flow And Voltage Drop Across Resistors In Simple Circuits

1.5.1 The Voltage Divider Formula in a Series Resistive Circuit

$$V_X = \frac{R_X}{R_T} * V_s$$

Where,

V_x is the voltage to be found,

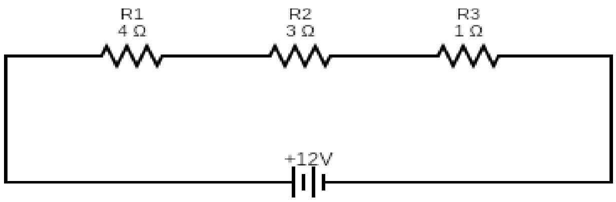
R_x is the resistance across which, the voltage is to be found

R_T is the total series resistance and

V_S is the supply voltage.

1.5.2 Voltage Drop and Current Calculation in a Series Circuit

Find the voltages drop across each resistor are connected in series and find total current flow in circuit that can be fed from a 12-V battery shown in the figure below with the help of a voltage divider circuit.



Solution

The total resistance in the circuit: $R_{total} = R_1 + R_2 + R_3$

$= 4 + 3 + 1$

$= 8\ \Omega$

Drop across $V_{R1} = \frac{4}{8} * 12 = 6$ V.

Drop across $V_{R2} = \frac{3}{8} * 12 = 4.5$ V.

Drop across $V_{R3} = \frac{14}{8} * 12 = 1.5$ V.

Total Voltage Drop = Sum of Voltage drop across each Resistor

= 6V + 4.5V + 1.5V

Total Voltage Drop = 12V

1.5.3 Total Circuit Current Calculation

Apply Ohm's law i.e.: V=I*R

Current (I) = Voltage (V) / Resistance (R)

= 12V/ 8Ω

= 1.5 Amperes

1.5.4 The Current Divider Formula in a Parallel Resistive Circuit

$I_x = \frac{R_T}{R_T+R_X} * I_T$

Where,

I_x = Current through any resistor in the parallel circuit

I_T = Total current of the circuit

R_T = Equivalent resistance of the parallel circuit

R_x = Resistance through which current I_x passes

1.6 The Wheatstone Bridge

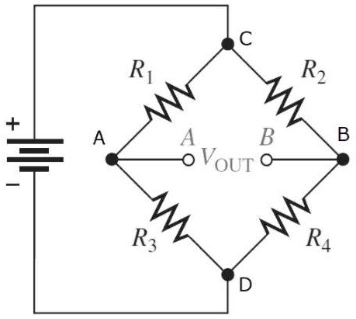
A wheatstone bridge network or circuit is one of the most popular electrical tools that is often used in measurement circuits, transducer circuits, switching circuits and also in oscillators.

As the wheatstone bridge is one of the most common and simplest bridge network / circuit, it can be used to measure resistance very precisely. But often the wheatstone bridge is used with transducers to measure physical quantities like temperature, pressure, strain, salinity, liquid level, etc.

A Wheatstone Bridge is used in applications where small changes in resistance are to be measured in sensors. This is used to convert a change in resistance to a change in voltage of a transducer. The combination of this bridge with an operational amplifier is used extensively in industries for various transducers and sensors.

For example, the resistance of a Thermistor changes when it is subjected to change in temperature. Likewise, with a strain gauge, when it is subjected to pressure, force or displacement, its resistance changes. Depending on the type of application, the Wheatstone Bridge can be operated either in a Balanced condition or an Unbalanced condition.

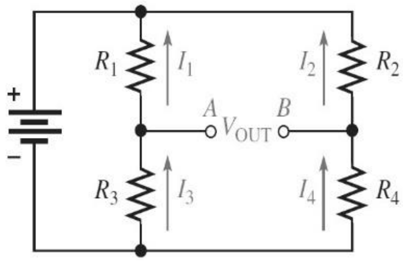
It consists of four resistors (R_1, R_2, R_3 and R_4) that are connected in the shape of a diamond with the DC supply source connected across the top and bottom points (C and D in the circuit) of the diamond and the output is taken across the other two ends (A and B in the circuit).



This bridge is used to find the unknown resistance very precisely by comparing it with a known value of resistances. In this bridge, a Null or Balanced condition is used to find the unknown resistance. For this bridge to be in a Balanced Condition, the output voltage at points A and B must be equal to 0. From the above circuit:

The Bridge is in Balanced Condition if: $V_{out} = 0V$

To simplify the analysis of the above circuit, let us redraw it as follows:



Now, for a balanced condition, the voltage across the resistors R_1 and R_2 is equal. If V_1 is the voltage across R_1 and V_2 is the voltage across R_2, then:

$V_1 = V_2$

Similarly, the voltage across resistors R_3 (let us call it V_3) and R_4 (let us call it V_4) are also equal. So,

$V_3 = V_4$

The ratios of the voltage can be written as:

$$\frac{V_1}{V_3} = \frac{V_2}{V_4}$$

From Ohm's law, we get:

$$\frac{I_1 R_1}{I_3 R_3} = \frac{I_2 R_2}{I_4 R_4}$$

Since $I_1 = I_3$ and $I_2 = I_4$, we get:

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

From the above equation, if we know the values of three resistors, we can easily calculate the resistance of the fourth resistor.

1.6.1 Finding an Unknown Resistance using a Balanced Wheatstone Bridge

In the above circuit, let us assume that R_1 is an unknown resistor. So, let us call it R_X. The resistors R_2 and R_4 have a fixed value. Which means, the ratio R_2 / R_4 is also fixed. Now, from the above calculation, to create a balanced condition, the ratio of resistors must be equal i.e.,

$$\frac{R_X}{R_3} = \frac{R_2}{R_4}$$

Since the ratio R_2 / R_4 is fixed, we can easily adjust the other known resistor (R_3) to achieve the above condition. Hence, it is important that R_3 is a variable resistor, which we call R_V.

But how do we detect the balanced condition? This is where a galvanometer (an old school ammeter) can be used. by placing the galvanometer between the points A and B, we can detect the balanced condition.

With R_X placed in the circuit, adjust the R_V until the Galvanometer points to 0. At this point, note down the value of R_V. By using the following formula, we can calculate the unknown resistor R_X.

$$R_X = R_V * \frac{R_2}{R_4}$$

1.6.2 Applications

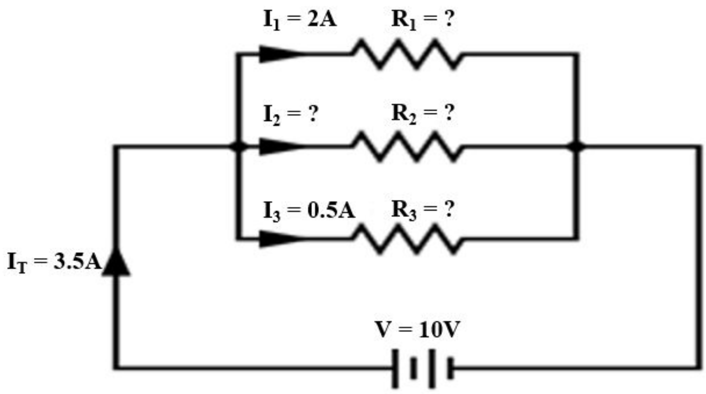
The Wheatstone Bridge is used for measuring the very low resistance values precisely.

A Wheatstone bridge along with an operational amplifier is used to measure physical parameters like temperature, strain, light, etc.

We can also measure the quantities capacitance, inductance and impedance using the variations on the Wheatstone Bridge.

1.7 Calculating The Total (Or Equivalent) Resistance Of A Parallel Circuit With A Given Voltage And Total Current

Find the unknown circuit parameters and power delivered by a 10v battery for the simple parallel circuit shown below:



Solution: To find I_2

$I_T = (I_1 + I_2 + I_3)$

$3.5\ A = (2\ A + I_2 + 0.5\ A)$

$I_2 = 1\ A$

To find R_1, R2, R3 =?

$R_1 = \frac{V}{I_1} = \frac{10}{2} = 5\ \Omega$

$R_2 = \frac{V}{I_2} = \frac{10}{1} = 10\ \Omega$

$R_3 = \frac{V}{I_3} = \frac{10}{0.5} = 20\ \Omega$

To find R_{total} =?

$$\frac{1}{R_{total}} = \frac{1}{5} + \frac{1}{10} + \frac{1}{20}$$

$R_{total} = 2.85\ \Omega$

The power delivered by a 10 V battery

$P = V * I$

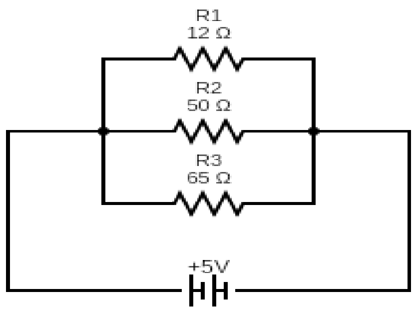
$= 10 * 3.5$

$\therefore P = 35W$

1.8 Given the values of resistances in a parallel circuit, calculate the total resistance

Problem

Find the equivalent resistance of parallel resistor circuit shown below:



Solution.

Total Resistance in circuit R_{total} =?

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_{total}} = \frac{1}{12} + \frac{1}{50} + \frac{1}{65}$$

$R_{total} = 8.42\ \Omega$

1.9 Effect of Adding a Further Resistance to A Series Circuit

When resistors are connected in series, the total voltage (or potential difference) across all the resistors is equal to the sum of the voltages across each resistor. In other words, the voltages around the circuit add up to the voltage of the supply.

Thus,

Adding more series resistors in a series circuit will increase the total resistance and the current will reduce.

The total resistance in series is given by:

$R_{total} = R_1 + R_2 + R_3$.

This is the equation for a series circuit. So the new total resistance will be greater than the existing total resistance.i.e., new total resistance is greater than the larger resistance in individual branch among all resistors in the circuit.

1.10 Effect of Adding A Further Resistance in A Parallel Circuit

When adding more parallel resistances to the paths, it causes the total resistance in the circuit to decrease. As you add more and more branches to the circuit, the total current will increase because Ohm's Law states that the lower the resistance, the higher the current.

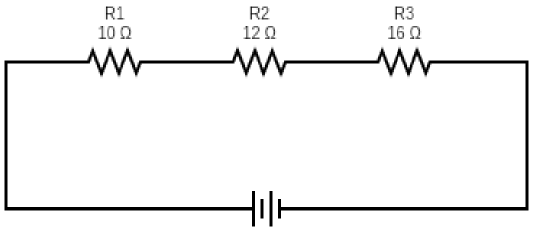
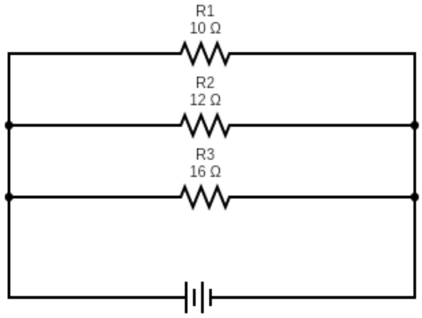
Explanation

Total resistance in parallel is given by:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This is the equation for parallel circuit. So new total resistance will lesser than the existing total resistance. i.e., new total resistance is lesser than the least resistance in individual branch among all resistors in a circuit.

1.11 Comparison between Series Resistance Circuit and Parallel Resistance Circuit

Series Resistance Circuit	**Parallel Resistance Circuit**
Circuit Diagram:  	**Circuit Diagram:** 
Formula for Series resistance calculations: $R_{total} = R_1 + R_2 + R_3$.	**Formula for Parallel resistance calculations:** $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$
Calculation: $R_{total} = 10\Omega + 12\ \Omega + 16\ \Omega$. $R_{total} = 38\ \Omega$	**Calculation:** $\frac{1}{R_{total}} = \frac{1}{10\Omega} + \frac{1}{12\Omega} + \frac{1}{16\Omega}$ $\mathbf{R_{total}} = 4.06\ \Omega$

1.12 Effect on the e.m.f and the terminal potential difference of a supply by calculations and by experiment

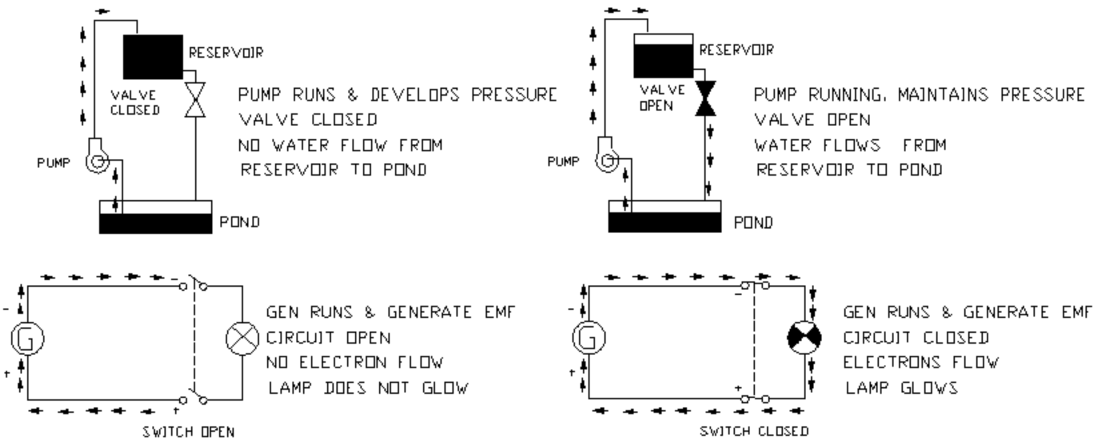
1.12.1 Electromotive Force

You can think of many different types of voltage sources. Batteries themselves come in many varieties. There are many types of mechanical/electrical generators, driven by many different energy sources, ranging from nuclear to wind. Solar cells create voltages directly from light, while thermoelectric devices create voltage from temperature differences.

A few voltage sources are hydel power generation, wind mill and battery cells. All such devices create a potential difference and can supply current if connected to a resistance. On the small scale, the potential difference creates an electric field that exerts force on charges, causing current. We thus use the name electromotive force, abbreviated emf.

1.12.2 Hydraulic Analogy (Water-level Analogy)

EMF is not a force at all; it is a special type of potential difference. To be precise, the electromotive force (emf) is the potential difference of a source when no current is flowing. The unit of EMF is the volt.



Electromotive force is directly related to the source of potential difference, such as the particular combination of chemicals in a battery. However, emf differs from the voltage output of the device when current flows. The voltage across the terminals of a battery, for example, is less than the emf when the battery supplies current, and it drops further as the battery is depleted or loaded. However, if the device's output voltage can be measured without drawing current, then the output voltage will equal the EMF (even for a very depleted battery).

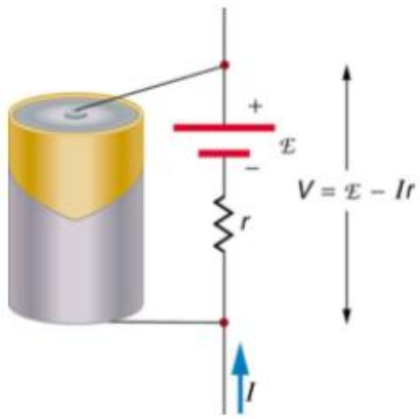
When you forget to turn off your car lights, they slowly dim as the battery runs down. Why don't they simply blink off when the battery's energy is gone? Their gradual dimming implies that battery output voltage decreases as the battery is depleted.

Furthermore, if you connect an excessive number of 12-V lights in parallel to a car battery, they will be dim even when the battery is fresh and even if the wires to the lights have very low resistance. This implies that the battery's output voltage is reduced by the overload.

The reason for the decrease in output voltage for depleted or overloaded batteries is that all voltage sources have two fundamental parts - a source of electrical energy and an internal resistance.

The internal resistance as noted in a 12-V truck battery is physically larger, and contains more charge and energy, and can deliver a larger current than a 12-V motorcycle battery. Both are lead-acid batteries with identical emf, but, because of its size, the truck battery has a smaller internal resistance r. Internal resistance is the inherent resistance to the flow of current within the source itself.

The figure shown below is a schematic representation of the two fundamental parts of any voltage source. The EMF (represented by E in the figure) and internal resistance r are in series. The smaller the internal resistance for a given emf, the more current and the more power the source can supply.



Any voltage source (in this case, a carbon-zinc dry cell) has an emf related to its source of potential difference, and an internal resistance ***r*** related to its construction. (Note that the script E stands for emf.).

Also shown are the output terminals across which the terminal voltage ***V*** is measured. Since $V = \text{emf} - Ir$, the terminal voltage equals emf only if there is no current flowing.

The internal resistance **r** can behave in complex ways. As noted, **r** increases as a battery is depleted. But internal resistance may also depend on the magnitude and direction of the current through a voltage source, its temperature, and even its history. The internal resistance of rechargeable nickel-cadmium cells, for example, depends on how many times and how deeply they have been depleted.

Why are chemicals able to produce a unique potential difference? Quantum mechanical descriptions of molecules, which take into account the types of atoms and numbers of electrons in them, are able to predict the energy states they can have and the energies of reactions between them.

In the case of a lead-acid battery, an energy of 2 eV is given to each electron sent to the anode. Voltage is defined as the electrical potential energy divided by charge: $V = \frac{P_E}{Q}$ An electron volt is the energy given to a single electron by a voltage of 1 V. So the voltage here is 2 V, since 2 eV is given to each electron. It is the energy produced in each molecular reaction that produces the voltage. A different reaction produces a different energy and, hence, a different voltage.

1.12.3 Terminal Voltage

The voltage output of a device is measured across its terminals and, thus, is called its terminal voltage V. Terminal voltage is given by:

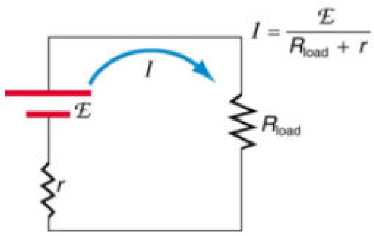
$$V = \text{emf} - IR$$

Where R is the internal resistance and I is the current flowing at the time of the measurement.

I is positive if current flows away from the positive terminal, you can see that the larger the current, the smaller the terminal voltage. And it is likewise true that the larger the internal resistance, the smaller the terminal voltage.

Suppose a load resistance R_{load} connected to a voltage source, as in shown in the figure below. Since the resistances are in series, the total resistance in the circuit is R_{load} +r. Thus, the current is given by Ohm's law to be:

$$I = \frac{emf}{r + R_{load}}$$



The schematic diagram of a voltage source and its load $\boldsymbol{R_{load}}$. Since the internal resistance ***r*** is in series with the load, it can significantly affect the terminal voltage and current delivered to the load. (Note that the script E stands for emf.)

We see from this expression that the smaller the internal resistance r, the greater the current the voltage source supplies to its load R_{load}. As batteries are depleted, r increases. If r becomes a significant fraction of the load resistance, then the current is significantly reduced, as the following example illustrates.

1.12.4 Calculating Terminal Voltage, power dissipation, Current and Resistance: Terminal voltage and load

A certain battery has a 12V emf and an internal resistance of 0.1Ω.

(a) Calculate its terminal voltage when connected to a 10Ω −Ω load.

(b) What is the terminal voltage when connected to a 0.5 −Ω load?

(c) What power does the 0.5 −Ω load dissipate?

(d) If the internal resistance grows to 0.5Ω,

Find the current, terminal voltage, and power dissipated by a 0.500−Ω load.

Strategy

The analysis above gave an expression for current when internal resistance is taken into account. Once the current is found, the terminal voltage can be calculated using the equation

V= emf − Ir. Once current is found, the power dissipated by a resistor can also be found.

Solution for (a)

Entering the given values for the emf, load resistance, and internal resistance into the expression above yields:

$I = \frac{emf}{r + R_{load}}$

$I = \frac{12\ v}{10.1\ \Omega} = 1.188\ A$

Entering the known values into the question V = emf − Ir to get the terminal voltage

$V = emf - I_r$

$= 12\ V - (1.188\ A)\ (0.1\Omega)$

$= 11.9\ V$

Discussion for (a)

The terminal voltage here is only slightly lower than the emf, implying that 10.0Ω10.0Ω is a light load for this particular battery.

Solution for (b)

Similarly, with $R_{load} = 0.500\Omega$, the current is

$I = \frac{emf}{r + R_{load}}$

$I = \frac{12\ v}{0.6\Omega}$

I = 20A

The terminal voltage is now

$V_{emf} - I_r = 12.0V - (20.0A)(0.100\Omega)$

$= 10v$

Discussion for (b)

This terminal voltage exhibits a more significant reduction compared with emf, implying 0.500Ω is a heavy load for this battery.

Solution for (c)

The power dissipated by the $0.500-\Omega$ load can be found using the formula ($P = I^2 R$). Entering the known values gives

$P_{load} = I^2 R_{load}$

$= (20\ A)^2 * (0.5\ \Omega)$

$= 2 * 10^2\ W$

Discussion for (c)

Note that this power can also be obtained using the expressions $\frac{V^2}{R}$ or V*I

Where:

V is the terminal voltage in this case (10v)

Solution for (d)

Here the internal resistance has increased, perhaps due to the depletion of the battery, to the point where it is as great as the load resistance. As before, we first find the current by entering the known values into the expression, yielding

$I = \frac{emf}{r + R_{load}}$ (latex)

$= \frac{12v}{1}$

$=12\ A$

Now the terminal voltage is:

$V_{emf} - I_r = 12v - (12.0A)\ (0.500\Omega) = 6V$

The power dissipated by the load is:

$P_{load} = I^2 * R_{load}$

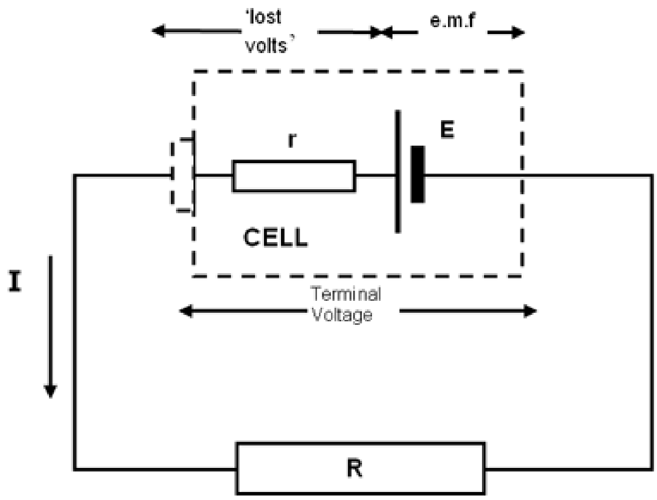
$= (12A)^2\ (0.5\Omega) = 72\ W$

Discussion for (d)

We see that the increased internal resistance has significantly decreased terminal voltage, current, and power delivered to a load.

1.13 Effect of Internal Resistance on The Supply Source

All power supplies have some resistance between their terminals called internal resistance. This causes charges in the circuit to dissipate some electrical energy in the power supply itself. The power supply becomes warm when delivering a current.



So ε = V + VR

Since I is a constant in a series circuit and V=IR

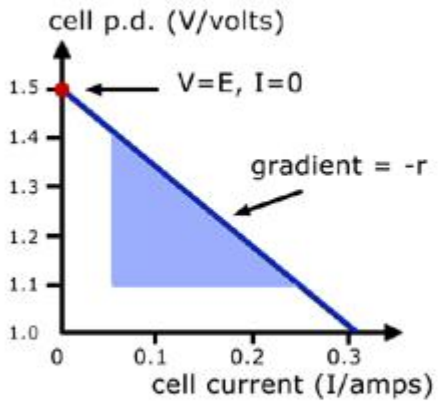
E = I(R+r) ε = I(R+r)

V_R is known as the terminal voltage and represents the 'useful' voltage that the power supply can output to the circuit.

VR = ε – IrVR=ε−Ir

V_R is the 'lost' voltage

If R is very small, it will end up sharing a good amount of the total EMF with the internal resistance. This will also lead to a higher current. The terminal voltage decreases.



If R is high, the terminal voltage will increase but the current will be lower.

It turns out that an EMF will deliver maximum power to the circuit when R is equal to r.

The potential difference across an EMF will drop as soon as current starts flowing as work is done against internal resistance.

If the voltage source is sitting there idle, not delivering any current, then the effects of its internal resistance is zero. There is no effect. Resistance is only defined by current flowing through a conductor, and since no current is flowing, in theory there is no resistance. Since there is no resistance (it's effect is multiplied by zero so it's zero), the voltage on the source's terminals is the voltage of the source. That voltage depends then on what created that source, perhaps the amount of light on a solar cell, or the chemistry in a battery, or the rotation of a generator.

When we attempt to measure that voltage, at least some current has to flow into the meter, so now we begin to see an effect. Something like a modern digital DMM will draw very little current, and in most cases the effect on the voltage on the source's terminals is so insignificant that it is usually okay to ignore it.

If we were to use an analog meter, there will be a noticeable difference. The current in the meter coils will cause the terminal voltage to reduce. Old meters generally have some indication on the meter showing ohms per volt. That is an attempt to compensate for the measurement error by indicating how much it will load a voltage source; this can be called parasitic load and in ships - especially for instrumentation panels, the parasitic load in VA will be mentioned.

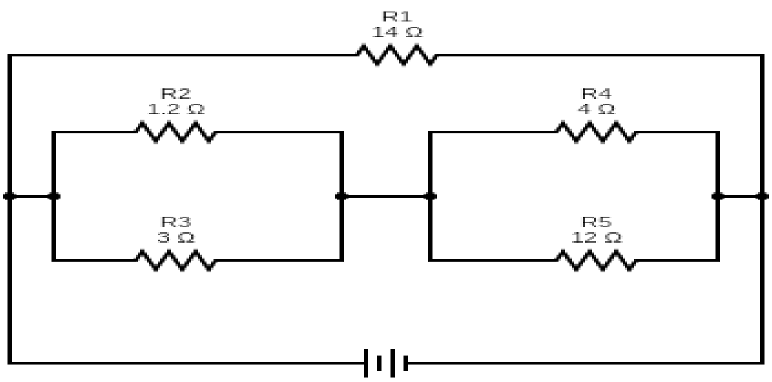
If we use something suchas low-tech as a tungsten light bulb, we will be able to estimate the voltage based on how bright the light is, but that is often a heavy load for some weaker voltage sources. For example, an old flashlight battery may only produce an orange glow - showing a high internal resistance of the source because little current is available to heat the filament. Change to a fresh, new battery and the lamp glows white-hot. That's because a new battery will have a much lower internal resistance, so the terminal voltage is much higher.

The internal resistance for many voltage sources does not actually exist, although some devices that supply voltage do have a current limiting resistor. Mostly though, internal resistance is only used as a method to calculate how the terminal voltage is loaded down when a load is applied. The actual voltage drop is affected by the load (it's resistance), and the theoretical internal resistance of the source. Calculating this voltage change is as simple as applying Ohm's law.

In short, the effects of internal resistance on a voltage source are to reduce its ability to supply a current. More internal resistance causes less current, because more internal resistance causes the terminal voltage to reduce proportional to the amount of load connected. No load (infinite resistance) = no effect, while absolute maximum load (short-circuit or zero ohms) = reduces the terminal voltage to zero for maximum effect.

1.14 Determination of current flows, resistance values and voltages in series circuits and parallel circuits by calculation

Find the Voltage across the battery, it supplies 47.64 W power and 3.97 A current to load resistance are shown in the below circuit, also find equivalent resistance and Voltage drop across resistors R_2R_3 and R_4R_5.



Solution:

Voltage across the Battery:

We know that formula

$$\mathbf{P = V * I}$$

$$V = \frac{P}{I} = \frac{47.64}{3.97}$$

$$V = 11.99 \approx 12v$$

Equivalent circuit resistance:

We know that

Series resistance calculation: $R_{total} = R_1 + R_2 + R_3$

Parallel resistance calculation: $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

$R_{Total} = (R_1) // ((R_2 // R_3) + (R_4 // R_5))$

$= (14\Omega) // ((1.2\Omega // 3\Omega) + (4\Omega // 12\Omega))$

$= (14\Omega) // ((0.8571) + (3\Omega))$

$= (14\Omega) // (3.8571\Omega)$

$R_{Total} = 3.02\ \Omega$

To find the voltage drop across resistor $R_2 R_3$ and $R_4 R_5$.

Resistor R_2 and R_3 are parallel, so voltage drop across each resistor R_2 R_3 are same.

Consider R_2R_3 as R_A

$$\frac{1}{R_A} = \frac{1}{1.2\Omega} + \frac{1}{3\Omega}$$

$R_A = 0.85\Omega$

Consider R_4R_5 as R_B

$$\frac{1}{R_B} = \frac{1}{4\Omega} + \frac{1}{12\Omega}$$

$R_B = 3\Omega$

Voltage drop across R_A and R_B

We know that:

$$V_X = \frac{R_X}{R_T} * V_s$$

$V_A = \frac{0.85\Omega}{0.85\ \Omega + 3\Omega} * 12$

$V_A = 2.64v$

$V_B = \frac{3\Omega}{3\ \Omega + 0.85\Omega} * 12$

$V_B = 9.35v$

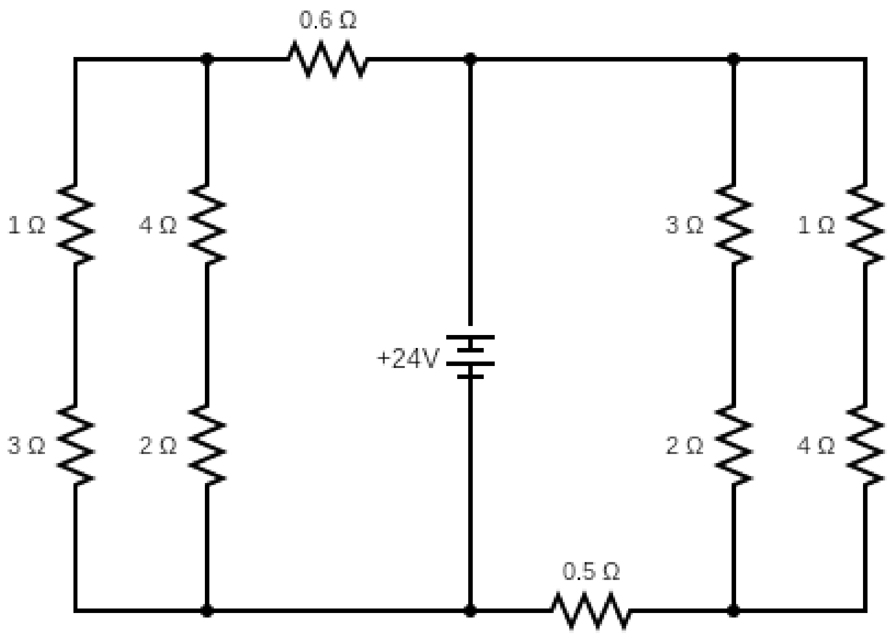
Problem 6:

The diagram below shows a circuit with one battery and 10 resistors; 5 on the left and 5 on the right. Determine:

i)The current through each resistor.

ii) The power dissipated by each resistor.

iii) The power delivered by the 24V battery source.



Let's begin the process by combining resistors. there are four series pairs in this circuit.

Left Right

$R_s = 3\ \Omega + 1\ \Omega$ $R_s = 2\ \Omega + 3\ \Omega$

$R_s = 4\ \Omega$ $R_s = 5\ \Omega$

$R_s = 4\ \Omega + 2\ \Omega$ $R_s = 1\ \Omega + 4\ \Omega$

$R_s = 6\ \Omega$ $Rs = 5\ \Omega$

These pairs form two parallel circuits, one on the left and one on the right.

Left Right

$$\frac{1}{R_p} = \frac{1}{4\Omega} + \frac{1}{6\Omega}\ \frac{1}{R_p} = \frac{1}{5\Omega} + \frac{1}{5\Omega}$$

$\frac{1}{R_p} = \frac{5}{12\Omega}$ $\frac{1}{R_p} = \frac{2}{5\Omega}$

$R_p = 2.4\Omega$ $R_p = 2.5\Omega$

Each gang of four resistors is in series with another.

Left Right

$R_s = 2.4\ \Omega + 0.6\ \Omega$ $R_s = 2.5\ \Omega + 0.5\ \Omega$

$R_s = 3\ \Omega$ $R_s = 3\ \Omega$

The left and right halves of the circuit are parallel to each other and to the battery.

$\frac{1}{R_p} = \frac{1}{3\Omega} + \frac{1}{3\Omega} = \frac{2}{3\Omega}$

$R_p = 1.5\Omega$

Now that we have the effective resistance of the entire circuit, let's determine the current from the power supply using Ohm's law.

$I_{total} = \frac{V}{R_{total}}$

$= \frac{24\ V}{1.5\ \Omega}$

$= 16A$

The left and right halves of the circuit are identical in overall resistance, which means the current will divide evenly between them.

8 A for the 0.6 Ω resistor on the left.

8 A for the 0.5 Ω resistor on the right.

On each side the current divides again into two parallel branches.

i)To find the current through those two resistors using the Current Divider formula:

$$I_x = \frac{R_T}{R_T + R_X} * I_T$$

For the 1 Ω and 3 Ωresistors series connection on the left.

$I_{3\Omega,\,1\Omega} = \frac{(2\,\Omega + 4\Omega)}{(2\,\Omega + 4\Omega) + 4\Omega} * 8$ $I_{3\Omega,\,1\Omega} = 4.8A$

For the 4 Ω and 2 Ωresistors series connection on the left.

To find the current through those two resistors

$I_{4\Omega,\,2\Omega} = \frac{(1\,\Omega + 3\Omega)}{(1\,\Omega + 3\Omega) + 6\Omega} * 8$

$I_{4\Omega,\,2\Omega} = 3.2A$

For the 2 Ω and 3 Ωresistors series connection on the right.

To find the current through those two resistors

$I_{2\Omega,\,3\Omega} = \frac{(4\Omega + 1\Omega)}{(4\,\Omega + 1\Omega) + 5\Omega} * 8$

$I_{2\Omega,\,3\Omega} = 4A$

For the 1 Ω and 4 Ωresistors series connection on the right.

To find current through those two resistors

$I_{1\Omega,\,4\Omega} = \frac{(3\Omega + 2\Omega)}{(3\,\Omega + 2\Omega) + 5\Omega} * 8$

$I_{1\Omega,\,4\Omega} = 4A$

ii) The power dissipated by each resistor using the formula for Power dissipation:

$P = I^2 * R$

Where:

P = Power in Watts

I = Current through the resistor in amperes

R = Value of resistor in ohms

We know that current flow through each resistor in circuit:

Left: Power dissipation in each resistor are tabulated as below by using power dissipation formula

Value of the resistor in Ω	Current through each resistor in Amps	Power Dissipation in each resistor in Watts
0.6	8	38.4
1	4.8	23.04
2	3.2	20.48
3	4.8	69.12
4	3.2	40.69

Right: Power dissipation in each resistor are tabulated as below by using power dissipation formula

Value of the resistor in Ω	Current through each resistor in Amps	Power Dissipation in each resistor in Watts
0.5	8	32
1	4	16
2	4	32
3	4	48
4	4	64

iii) The power delivered by a 24 V Battery source is P = V * I

= 24 * 16

= 384 Watts

Or

The power delivered by a 24 V battery source = The sum of all power dissipations in each resistor in the circuit

= 38.40+23.04+20.48+69.12+40.96+32+16+32+48+64

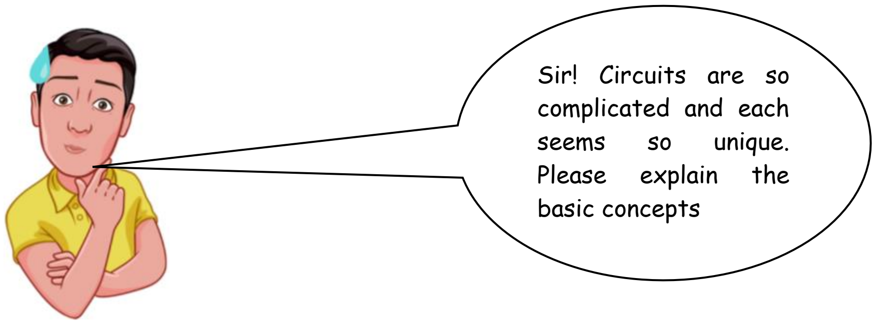
= 384 Watts

Chapter 1

Interesting Sites to Visit (No material has been downloaded for or used in this Chapter)

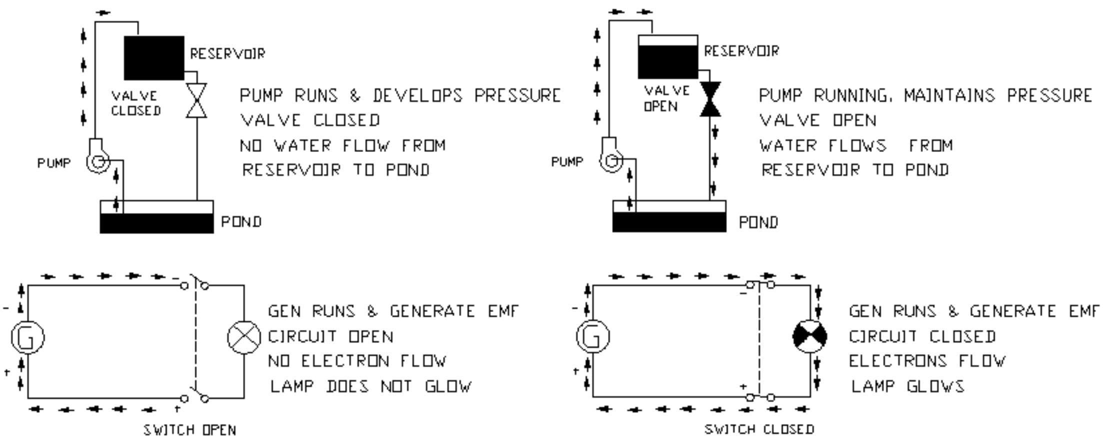
a) Electrical Technology.org
b) Electrical-engineering-portal.com
c) Engineeringtoolbox.com
d) Pdfprof.com
e) Slideshare.net

Chapter 2
Concepts of Electrical Circuits



Chapter 2

2.1 Current Flow in A Closed Circuit



2.2 Differences between Conductors and Insulators

2.2.1 What are Conductors?

If you have to give the simplest definition of electrical conductors, they are materials that allow electricity to flow easily through them. If we compare two kinds of materials and the first one allows electricity to pass through it more readily, then that material is said to be a strong conductor of electricity.

Also, conductors allow heat to be transmitted through them. The examples of conductors are metals, the human body, the earth and animals. The human body is a strong conductor. It, therefore, offers a low-resistance path from a current-carrying wire through the body for the current to flow. Conductors have free electrons that allow the easy passage of current. This is the reason why electricity is transmitted easily through conductors.

2.2.2 Properties of an Electrical Conductor

In equilibrium conditions, a conductor exhibits the following properties:

a) The movement of electrons and ions in them is permitted by a conductor.
b) A conductor's electrical field is zero, allowing electrons to pass inside it.
c) A conductor's charge density is zero.
d) Free charges occur only on the surface of the conductor.
e) Both of a conductor's ends are at the same potential.
f) Many metals are strong conductors of electricity.

Some random examples of the conductors of electricity are:

a) Copper
b) Aluminium
c) Silver
d) Gold
e) Graphite
f) Platinum
g) Water

An electric conductor enables electrical charges to pass through them easily. The property of conductors is called conductivity to "conduct" electricity. Such materials offer less opposition to the movement of charges, or "resistance." Due to the free movement of electrons through them, conducting materials allow easy charge transfer.

2.2.3 Other Applications of Conductors

In certain aspects, conductors are very useful in other areas of engineering. They have many real-life applications namely:

- To check the temperature of a body, mercury is a common material in the thermometer.
- Aluminium finds use in the manufacture of foils for food preservation. It is also used in cooking vessels as it is a good conductor of electricity and heat.
- Iron is a common material used to conduct heat in vehicle engine manufacturing. The iron plate is composed of steel to briskly absorb heat.
- In car radiators, conductors find their use in the eradication of heat away from the engine.

2.2.4 Insulators

The materials or substances that resist or don't allow the current to pass through them are insulators. They are, in general, solid in nature but could be very flexibe too, as in the case of the insulating material for cables and wires. Often, in a number of systems, insulators are used as they do not allow heat to flow. The resistivity is the property which makes insulators different from conductors.

2.2.5 Examples of Insulators

Some good examples of insulators are wood, fabric, glass, mica, and quartz. Insulators provide protection against fire, sound, and, of course, electricity transmission. In addition, insulators have no free electrons at all. This is the predominant explanation of why they don't conduct electricity.

- As it has the highest resistivity, glass is the strongest insulator.
- Plastic is a good insulator and is used to manufacture a variety of products.
- A common material used in the manufacture of tyres, fire-resistant clothing, and slippers is rubber. This is because it is an insulator.

2.3 Different Sources of Electrical Energy

The different sources of electrical energy are:

a) Solar Energy. The primary source of energy is the sun.

b) Wind Energy. Wind power is becoming more and more common.

c) Geothermal Energy.

d) Hydrogen Energy.

e) Tidal Energy.

f) Wave Energy.

g) Hydroelectric Energy.

h) Biomass Energy.

2.4 Potential Difference and Electromotive Force

There can be a lot of confusion between electromotive force, EMF and the voltage or potential difference, PD, at a point in an electrical or electronic circuit. Both EMF and potential difference are measured in volts, but the two parameters are very different.

These differences can be important in some aspects of electrical and electronic circuit design. It helps to have an understanding about what they are so, that confusion can be reduced and the correct terms and terminology is used where it is needed.

2.4.1 Electromotive force, EMF

Electromotive force is defined as the characteristic of any energy source capable of driving electric charge around a circuit - it is the force within a voltage source that drives the current around a circuit. It is abbreviated E in the international metric system but the abbreviation EMF is also widely used.

2.4.2 Potential Difference

The potential difference between two points in an electrical or electronic circuit represents the work involved or the energy released in the transfer of a unit quantity of electricity from one point to the other.

2.4.3 Similarities and Differences of EMF and Potential Difference

Electromotive Force (EMF)	Potential Difference (PD)
EMF is the driving electric force from a cell or generator.	Potential difference results from the current passing through a resistance within a circuit.
EMF is the cause.	Potential difference is the effect.
The EMF is also present even when no current is drawn through the battery.	Potential difference across the conductor is zero in the absence of current.
The unit of EMF is the volt.	The unit of potential difference is the volt.
EMF remains constant.	Potential difference does not remain constant - it depends upon the circuit conditions.
Its symbol is E.	Its symbol is V.
It does not depend on circuit resistance.	It depends on the resistance between two points of measurement.

EMF and potential difference have many similarities, but they also have some significant differences. Essentially the EMF is the driving force in a circuit, whereas the potential difference is the result of the EMF within a circuit to which the source is connected

2.5 Current Flow

An electric current is a flow of electric charge in a circuit. More specifically, the electric current is the rate of charge flow past a given point in an electric circuit.

The charge can be negatively charged electrons or positive charge carriers including positive ions or holes.

2.5.1 The Basics

The basic concept of current is that it is the movement of electrons within a substance. Electrons are minute particles that exist as part of the molecular structure of materials. Sometimes these electrons are held tightly within the molecules and other times they are held loosely and they are able to move around the structure relatively freely.

One very important point to note about the electrons is that they are negatively charged charged particles. If they move then an amount of charge moves and this is called current.

It is also worth noting that the number of electrons that able to move governs the ability of a particular substance to conduct electricity.

Some materials allow current to move better than others. The motion of the free electrons is normally very haphazard - it is random - as many electrons move in one direction as in another and as a result there is no overall movement of charge.

Conventional current flow **Electron flow**

2.5.2 Current Strength Is Measured in Amperes, Represented by A

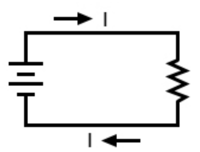
The magnitude of the electric current is measured in coulombs per second, the common unit for this being the Ampere or amp which is designated by the letter 'A'. Current flow in a circuit is normally designated by the letter 'I', and this letter is used in equations like Ohms law where $V = I \cdot R$.

In 2018 the General Conference on Weights and Measures (CGPM) agreed that on May 20, 2019, the ampere would henceforth be defined such that the elementary charge would be equal to 1.602176634 × 10−19 coulomb. Earlier the ampere was defined as the constant current which, if maintained in two straight parallel conductors of infinite length of negligible circular cross section and placed one metre apart in a vacuum, would produce between these conductors a force equal to 2 × 10−7 newton per metre of length. Named for 19th-century French physicist André-Marie Ampère, it represents a flow of one coulomb of electricity per second. A flow of one ampere is produced in a resistance of one ohm by a potential difference of one volt.

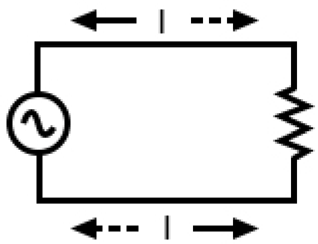
2.5.3 Direct Current (D.C.)

Direct current (DC) is the one directional flow of electric charge. An electrochemical cell is a prime example of DC power. The voltage in a direct-current circuit must be constant, or at least relatively constant, to keep the current flowing in a single direction.

The positive end of the battery is always positive relative to the negative end, and the negative end of the battery is always negative relative to the positive end. This constancy is what pushes the electrons in a single direction.



Direct Current



Alternating Current

2.5.4 Alternating Current (A.C.)

Alternating current (AC) is an electric current that periodically reverses its direction, in contrast to direct current (DC) which only flows in a single direction, which cannot change sporadically. Alternating current describes the flow of charge that changes direction periodically. As a result, the voltage level also reverses along with the current. AC is used to deliver power to houses, office buildings, etc.

2.5.5 Main Supply in Modern Ships

A ship is equivalent to a floating city that enjoys almost all privileges available to any operational set-up on land. Just like any conventional city, the ship also requires the basic amenities to sustain life on board, the chief among them being power or electricity. Electricity on modern ships is generated by an alternator.

Due to the merits of alternationg current, which is easy to transmit, step up and stp down, convert and manipulate, the main supply in modern ships is usually A.C. but D.C. has many uses as in the case of conventional submarines that still use batteries for their main source of power. DC is also used on board as the back-up source for alarms and critical electronic equipment.

2.5 Static Electricity

When two dissimilar materials are rubbed together, one may give up its electrons and other may receive these electrons. The material that gives up electrons becomes positively charged. And the one that receives electrons becomes negatively charged.

When two objects, one positively and other negatively charged come together, the extra electrons from the negatively charged object would move to the positively charged object. This is because of nature of it trying to attain equilibrium. This flow of electrons (charge) is also called static electricity. It can thus be concluded that static electricity is an electrical charge that cannot move.

It is also created when two objects or materials that have been in contact with each other are separated. When they are in contact, the surface electrical charges of the objects try to balance each other; this happens by the free flow of electrons (negatively charged particles) from one object to the other. When the objects separate, they are left with either an excess or a shortage of electrons.

2.5.1 Electrostatic Charging and The Principles of Overcoming Potential Hazards

Materials are made of atoms that are normally electrically neutral because they contain equal numbers of positive charges (protons in their nuclei) and negative charges (electrons in “shells“ surrounding the nucleus). The phenomenon of static electricity requires a separation of positive and negative charges.

When two materials are in contact, electrons may move from one material to the other, which leaves an excess of positive charge on one material, and an equal negative charge on the other.

When the materials are separated, they retain this charge imbalance.

2.5.1.1 Contact-induced charge separation

Electrons can be exchanged between materials on contact; materials with weakly bound electrons tend to lose them while materials with sparsely filled outer shells tend to gain them. This is known as the triboelectric effect and results in one material becoming positively charged and the other negatively charged. The polarity and strength of the charge on a material once they are separated depends on their relative positions in the triboelectric series.

2.5.1.2 Pressure-Induced Charge Separation

Applied mechanical stress generates a separation of charge in certain types of crystals and ceramics molecules.

2.5.1.3 Heat-Induced Charge Separation

Heating generates a separation of charge in the atoms or molecules of certain materials. All pyroelectric materials are also piezoelectric. The atomic or molecular properties of heat and pressure response are closely related.

2.5.1.4 Charge-induced Charge Separation

A charged object brought close to an electrically neutral object causes a separation of charge within the neutral object. Charges of the same polarity are repelled and charges of the opposite polarity are attracted. As the force due to the interaction of electric charges falls off rapidly with increasing distance, the effect of the closer (opposite polarity) charges is greater and the two objects feel a force of attraction.

2.5.2 *Some Dangers Posed by Static Electricity*

If these charges don't have a path to the ground, they are unable to move and become "static". If static electricity is not rapidly eliminated, the charge will build up. It will eventually develop enough energy to jump as a spark to some nearby grounded or less highly charged object in an attempt to balance the charge.

A good example of this in everyday life is lightning. Lightning is produced by a discharge of electricity from one cloud across an air gap to another cloud or between a cloud and the earth. In short, the process of static electricity generation has three stages namely:

1. Charge separation
2. Charge accumulation
3. Electrostatic discharge

2.5.2.1 Charge Separation

It is the first step for static electricity generation when two different materials like a conductor and an insulator comes in contact, electrons may move from one material to another where one material is able to give an electron or more away and other to be able to receive the same.

If subsequently the two materials become separated by some mechanical means, one will carry an excess of positive charge and the other an excess of negative charge.

As an example, on board tankers charge separation can happen because of friction between the cargo and the pipeline during the flow of cargo. In this case, the pipeline loses the electron and the cargo gains the electron to becomes negatively charged. Friction between the cargo and tank top because of splashing on the tank top, it gives electrons and the cargo gains the electrons during the initial stages of loading.

Other examples can be possible when two immiscible liquids are mixed together, charge separation can take place and when steam which is an insulator, flows through the steam pipe, it attains a negative charge. The separated charges will then try to recombine by conduction.

If one of the bodies is a poor conductor of electricity, recombination will be limited and a difference in charge or a difference in potential will exist between the two bodies; for example, a liquid becomes charged when it passes through pipes and water droplets become charged during tank cleaning.

Pure gases themselves do not become charged, but the flow of gases containing particulates, however, can generate a high static charge.

2.5.5.2 Charge Accumulation

Whenever two dissimilar materials come in contact, electrons move from one surface to the other. As these materials are separated and more electrons remain on one surface than the other, one material takes on a positive charge and the other a negative charge.

Two conductors having separate charge potentials try to recombine and neutralize almost immediately.

The degree of charge accumulation on a body is a balance between the rate of charge generation and the rate of charge decay. If a significant accumulation of charge is to occur, the rate of charge decay must be slow, which requires a high resistance with respect to the earth.

This resistance is governed by the electrical conduction properties of the charged material; for solids, the unit is ohmmeters and for liquids the unit is picosiemens per meter.

2.5.5.2.1 Causes of Charge Accumulation

The following are the common causes:

- Dust transport – e.g., pneumatic transport of powders / solids.
- Pouring powders – e.g., pouring solids down chutes or troughs.
- Gears and belts – e.g., transporting charges from one surface to another.
- Synthetic materials like plastics have very high values of resistivity and can readily accumulate static charges.
- Refined petroleum products can have very low electrical conductivities like 1picosiemen / metre and can become charged during handling. But crude oil has a relatively high conductivity and does not accumulate a static charge.
- A water mist consisting of highly conductive droplets can accumulate a static charge because each particle is electrically isolated.

2.5.5.3 Electrostatic Discharge

Electrostatic discharge is a process of shifting of electrons from one material to another when two materials with opposite charge come in contact with each other.

The two charges need to have a minimum distance between them. This distance depends upon how strongly the materials are charged and how much are the voltage differences between them. More the voltage difference, higher is the energy released during electrostatic discharge.

2.6 Impedance and Inductance

2.6.1 Impedance

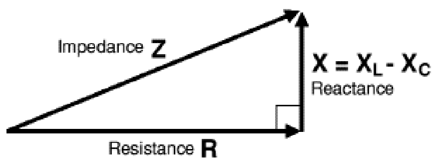
Electrical impedance is a measure of the total opposition that a circuit or a part of a circuit presents to electric current. Impedance includes both resistance and reactance. The resistance component arises from the collision of the current-carrying charged particles with the internal structure of the conductor.

The reactance component is an additional opposition to the movement of electric charge that arises from the changing magnetic and electric fields in circuits carrying alternating current. Impedance reduces to resistance in circuits carrying steady direct current.

The magnitude of the impedance Z of a circuit is equal to the maximum value of the potential difference, or voltage, V (volts) across the circuit, divided by the maximum value of the current I (amperes) through the circuit, or simply Z = V/I. The unit of impedance, like that of resistance, is the ohm.

Depending on the nature of the reactance component of the impedance (whether predominantly inductive or capacitive), the alternating current either lags or leads the voltage.

The reciprocal of the impedance, 1/Z, is called the admittance and is expressed in terms of the unit of conductance, the unit *mho*.



$$\textbf{Impedance,}\quad Z = \sqrt{R^2 + X^2}$$

2.6.2 Impedance of AC versus Resistance in DC

The opposition offered to the flow of current in an electric circuit whether AC or DC is known as the Resistance. The opposition offered to the flow of current in an AC circuit because of resistance, capacitance and inductance is known as Impedance.

Resistance is the contribution of the resistive element in the circuit, whereas the contribution of both resistance and reactance forms Impedance.

Resistance is denoted by (R) whereas impedance by (Z).

Resistance is a simple value consisting of only real numbers. Example: 3.4 Ω, 6.2 Ω, etc. Impedance comprises of both real and imaginary numbers. Example: R+ij, where R is a real number and ij is imaginary part.

The Resistance of the circuit does not vary according to the frequency of AC, whereas Impedance varies with the change in frequency of AC.

Impedance has both magnitude and phase angle, whereas Resistance does not have phase angle. Resistance, if kept in an electromagnetic field represents power dissipation in any material. Similarly, if Impedance is subjected to magnetic field it represents both power dissipation and energy storage.

2.6.3 Relationship between Voltage, Current, Impedance

Assuming a two-terminal circuit element with impedance Z is driven by a sinusoidal voltage or current as above, there holds V=IZ. The magnitude of the impedance |Z| acts just like resistance, giving the drop in voltage amplitude across an impedance Z for a given current I. The phase factor tells us that the current lags the voltage by a phase of a certain value.

Just as impedance extends Ohm's law to cover AC circuits, other results from DC circuit analysis, such as voltage division, current division, Thevenin's theorem and Norton's theorem, can also be extended to AC circuits by replacing resistance with impedance.

$$I = \frac{V}{Z}$$

$I = \frac{V}{R}$ for a pure resistor where Z=R, preserving the form of the DC Ohm's law.

2.6.4 Effects of Resistance and Inductance in AC and DC circuits

1. A Simple Resistance

The resistance offered by a conductor for both AC and DC is different, the resistance offered to DC by a conductor is known as DC resistance while the resistance offered to AC is known as AC resistance or effective resistance. For a given conductor AC resistance is more than its DC resistance. This is because an alternating current flowing through a conductor does not distribute uniformly but tends to concentrate near the surface of the conductor. The result is that effective area of the conductor is reduced, causing an increase in resistance.

2. An Inductor

It will basically behave and produce a short across itself when it is subjected to a DC, while offer an opposing or restricting response when it is applied with an AC. The magnitude of this opposing response or force of an inductor to an AC or alternating current is called the reactance of the inductor and depends upon the frequency and the value of inductance itself.

3. A Coiled Resistance with an Iron Core

It will be as above situation with the only major difference being the increase in magnetic flux being produced. In a DC circuit, it will continue to act as a short circuit.

2.6.5 What is Meant by Reactance?

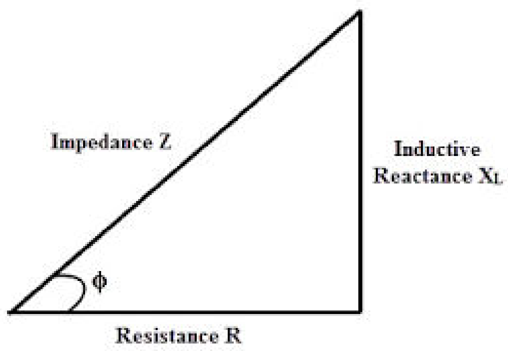
Reactance is a property that opposes a change in current and is found in both inductors and capacitors. Because it only affects changing current, reactance is specific to AC power and depends on the frequency of the current.

When reactance is present, it creates a 90^{O} phase shift between voltage and current, with the direction of the shift depending on whether the component is an inductor or a capacitor. Reactance that occurs in an inductor is known as inductive reactance $XL = 2\pi fL$. Reactance that occurs in a capacitor is known as capacitive reactance. Impedance is the combination of resistance and reactance, both inductive and capacitive. Capacitive reactance $XC = 1/2\pi fC$.

Impedance $Z = \sqrt{R^2 + (XL - XC)^2}$

$P_{avg} = VI \cos\phi$ in a single-phase circuit and $\sqrt{3}\, V\, I \cos\phi$ in a three-phase circuit.

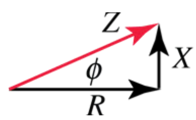
2.6.6 The Impedance Triangle



2.6.7 Power Factor

For a DC circuit the power is P = VI, and this relationship also holds for the instantaneous power in an AC circuit. However, the average power in an AC circuit expressed in terms of the rms voltage and current is where ϕ is the phase angle between the voltage and current. The additional term is called the power factor.

$$\text{POWER FACTOR} = \cos\phi = \frac{R}{Z}$$



From the phasor diagram for AC impedance, it can be seen that the power factor is R/Z. For a purely resistive AC circuit, R=Z and the power factor = 1.

2.6.8 Calculating the Impedance and Power Factor When Resistance and Reactance are Given

To calculate impedance, we need values of resistance and reactance. On having that using the formula above both impedance and power factor can be found.

2.6.9 Effect of Changing Current on Induced EMF

Induced emf is directly proportional to the magnetic flux associated with it. So magnetic flux is what is our concern with inducing an EMF.

As current through a coil changes the associated magnetic flux associated with it also changes. Thus, this affects the induced EMF. This is kind of a chain reaction and it all is connected. So, change is current ultimately affects the induced EMF.

2.6.10 Lagging Nature of Reactance

Inductors that cause reactance, react against a change in current, di/dt. This can be termed as electrical inertia.

The voltage that changes the current comes first in the inductor, and then the induced current (and flux) change. This can be shown in a phasor diagram. Also note that 90 electrical degrees out of phase only works for ideal inductors. Keeping this in mind, when a sinusoidal voltage is applied to an inductor, say,

$V = Vm*\sin(\omega t)$ or

$Vm*\sin(\omega t) = L(di/dt)$.

And we integrate on both sides and simplify.

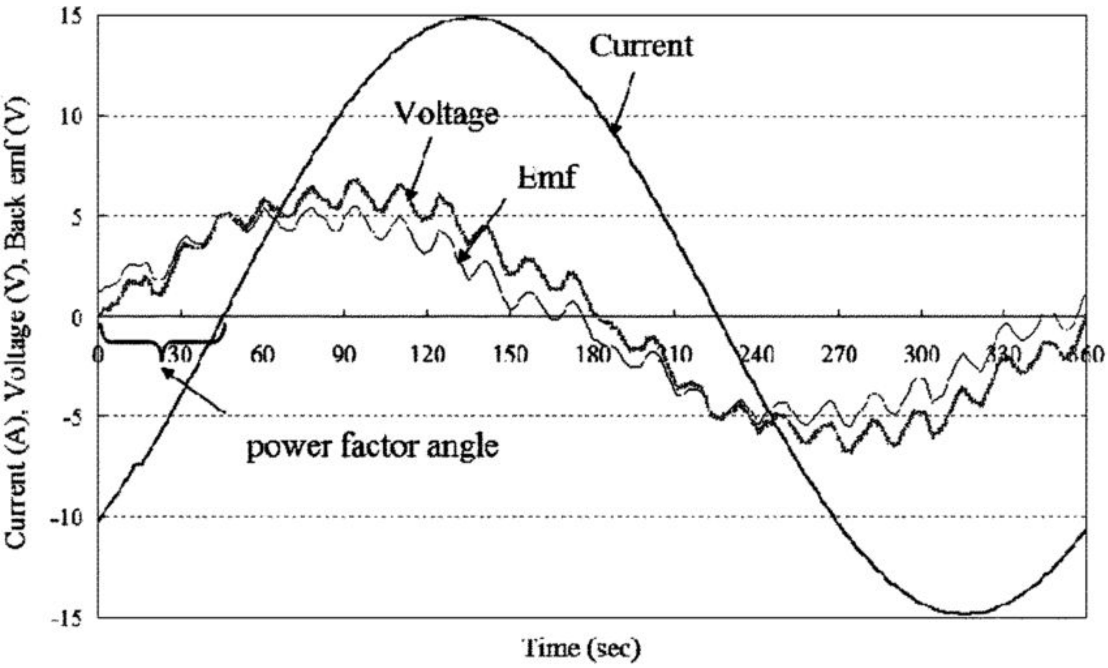
$i = (Vm/\omega L) * \cos\omega t$ or

$i = (Vm/\omega L) * \sin(\omega t - pi/2)$.

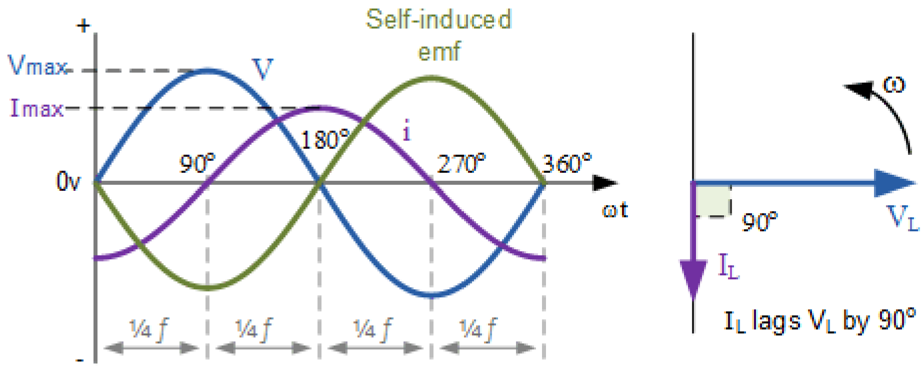
Thus, mathematically current lags voltage by 90^{O} electrical.

Note that in an alternator, 1^{O} of mechanical rotation = $({}^{P}/_{2})^{O}$ of electrical output , where P is the number of poles for the alternator.

2.6.11 Graph for Current, Voltage, Back EMF of a Resistive Circuit.



2.6.12 Graph for Current and Voltage of a Pure Inductive Circuit



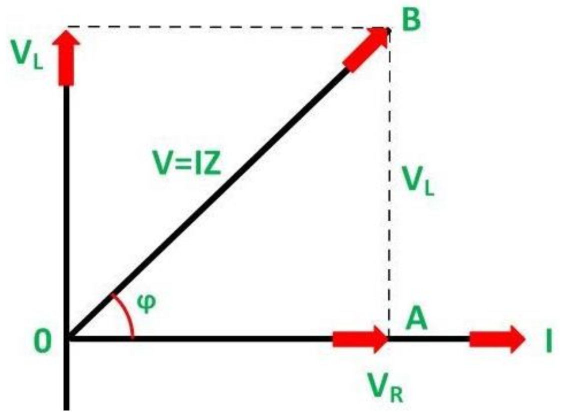
In practice, inductors will always have a resistance. The resistance of the wire is always present in an inductor, and as the frequency of an AC signal increases then the resistance actually increases due to the "skin effect". This is when a changing magnetic field forces the current to flow in the outer "skin" of the wire rather than uniformly through its cross-sectional area so the resistance goes up considerably.

Any real component will have resistance, inductance, and capacitance components. While the primary function of an inductor is to provide inductance the stray capacitance between the coils of wire can have a large effect on the circuit as signal frequencies go up.

The resistance of the wire will generate heat which can have an effect on the core of the inductor.

The resistance of an ideal inductor is zero. the inductor's impedance calculator calculates the impedance based on the value of the inductance, L, of the inductor and the frequency, *f*, of the signal passing through the inductor, according to the formula, XL= 2πfL.

2.6.13 Phasor Diagram of An Inductive Circuit with Resistance



2.6.14 Current Lag in Inductive Circuits

Lagging current can be formally defined as "an alternating current that reaches its maximum value up to 90^O later than the voltage that produces it." This means that current lags the voltage when the angle of the current sine wave with respect to an arbitrarily chosen reference, is less than the angle of the voltage sine wave with respect to the same reference.

Therefore, current can quickly be identified as lagging if the angle is positive. For example, if the voltage angle delta is zero, current will be lagging when delta is negative. This is often the case because voltage is taken as the reference.

In circuits with primarily inductive loads, current lags the voltage. This happens because in an inductive load, it is the induced electromotive force that causes the current to flow. Note that in the definition above, the current is produced by the voltage

2.6.15 Shipboard Installations Produce Lagging Power Demand

On board ships, the power factor is always lagging in nature because they are basically inductive in nature. A bulk of the machinery is run by motors – mostly of the induction-type. In addition, there are a lot of solenoids, lights with ballasts, etc.

2.6.16 Effect of Varying Power Factor on Power Consumed

Working Power – the “true” or “real” power used in all electrical appliances to perform the work of heating, lighting, motion, etc. We express this as kW or kilowatts. Common types of resistive loads are electric heating and lighting.

An inductive load, like a motor, compressor or ballast, also requires Reactive Power to generate and sustain a magnetic field in order to operate. We call this non-working power kVAR’s, or kilovolt-amperes-reactive.

Every home and business have both resistive and inductive loads. The ratio between these two types of loads becomes important as you add more inductive equipment. Working power and reactive power make up Apparent Power, which is called kVA, kilovolt-amperes.

Going one step further, Power Factor (PF) is the ratio of working power to apparent power, or the formula PF = kW / kVA. A high PF benefits both the customer and utility, while a low PF indicates poor utilization of electrical power.

Improving the PF can maximize current-carrying capacity, improve voltage to equipment, reduce power losses, and lower electric bills.

The simplest way to improve power factor is to add PF correction capacitors to the electrical system. PF correction capacitors act as reactive current generators. They help offset the non-working power used by inductive loads, thereby improving the power factor.

The interaction between PF capacitors and specialized equipment, such as variable speed drives, requires a well-designed system.

PF correction capacitors can switch on every day when the inductive equipment starts. Switching a capacitor on can produce a very brief "over-voltage" condition.

If a customer has problems with variable speed drives turning themselves off due to "over-voltage" at roughly the same time every day, investigate the switching control sequence. If a customer complains about fuses blowing on some but not all, of their capacitors, check for harmonic currents.

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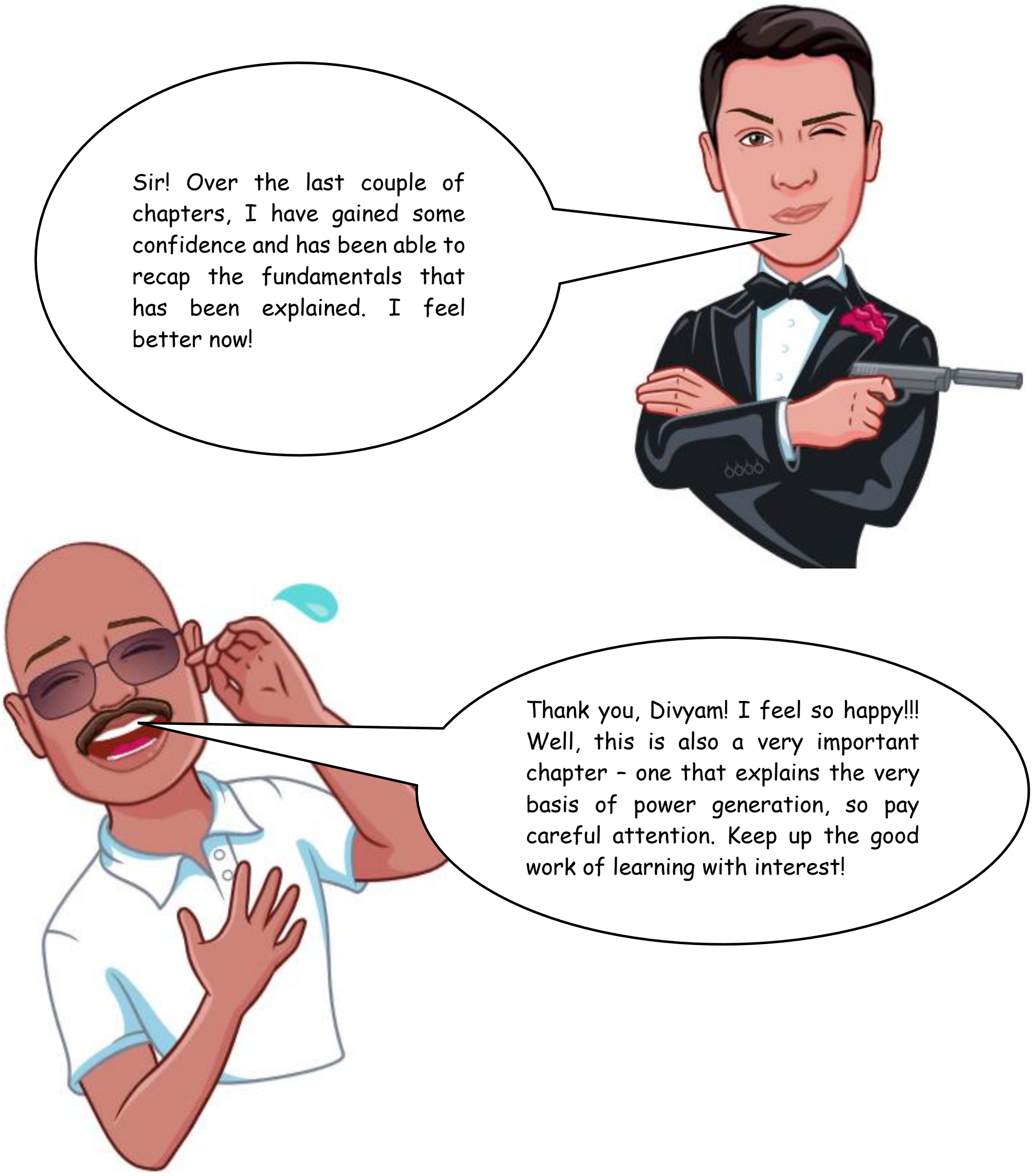
Chapter 3
Fundamentals of Alternating Current



Chapter 3

3.1 Production of AC in a Simple Conductor Loop Rotating in a Magnetic Field

When a magnetic field embracing a conductor moves *relative* to the conductor, it produces a flow of electrons in the conductor. This phenomenon whereby an e.m.f. and hence current (*i.e.* flow of electrons) is induced in any conductor which is cut across or is cut by a magnetic flux is known as ***electromagnetic induction***.

In Figure 3.1 an insulated coil is shown whose terminals are connected to a sensitive galvanometer *G.* It is placed close to a stationary bar magnet initially at position *AB* (shown dotted). As seen, someflux from the *N*-pole of the magnet is linked with or threads through the coil but, as yet, there is nodeflection of the galvanometer.

\Now, suppose that the magnet is suddenly brought closer to the coil in position *CD* (see figure). Then, it is found that there is a jerk or a sudden but a momentary deflection in the galvanometer and that this *lasts so long as the magnet is in motion relative to the coil, not otherwise.* The deflection is reduced to zero when the magnet becomes again stationary at its new position CD. It should be noted that due to the approach of the magnet, flux linked with the coil is increased.

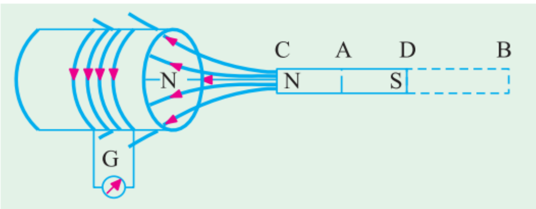


Figure 3.1

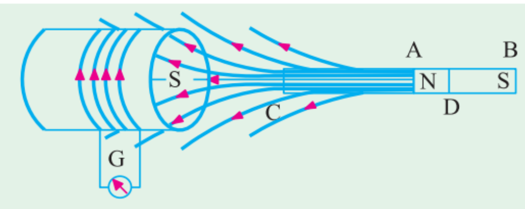


Figure 3.2

Next, the magnet is *suddenly* withdrawn away from the coil as in Fig. 3.2. It is found that again there is a *momentary* deflection in the galvanometer and it persists so long as the magnet is in motion, not when it becomes stationary. It is important to note that this deflection is in a direction opposite to that of Figure 3.1. Obviously, due to the withdrawal of the magnet, flux linked with the coil is decreased.

The deflection of the galvanometer indicates the production of e.m.f. in the coil. The only cause of the production can be the sudden approach or withdrawal of the magnet from the coil. It is found that the actual cause of this e.m.f. is the change of flux linking with the coil.

This e.m.f. exists so long as the change in flux exists. Stationary flux, however strong, will never induce any e.m.f. in a stationary conductor. In fact, the same results can be obtained by keeping the bar magnet stationary and moving the coil suddenly away or towards the magnet.

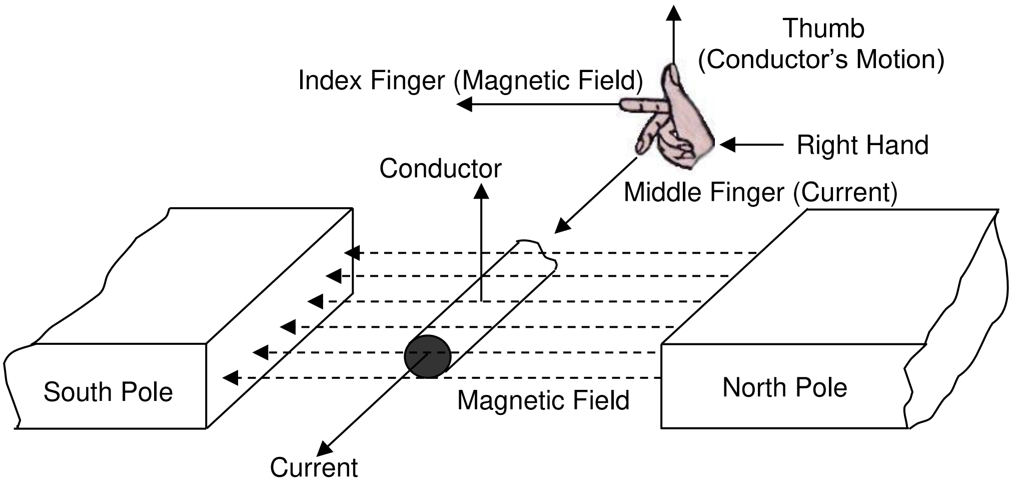
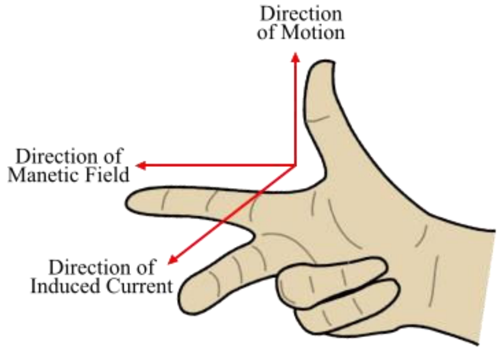


Figure 7.1 – Fleming's Right-Hand Rule

3.2 Fleming's Right-Hand Rule

Fleming's Right-Hand Rule is stated as follows:

"Stretch out the forefinger, middle finger and thumb of your right-hand so that they are at right angle from one another. If the forefinger points in the direction of magnetic field, the thumb point in the direction of motion of the conductor, then the middle finger will point in the direction of induced emf (or current)".

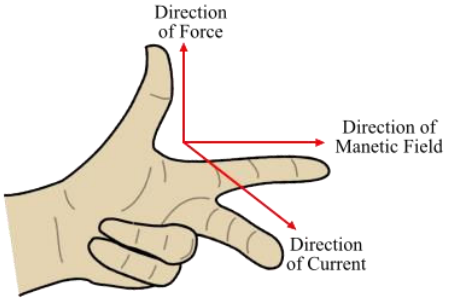


Fleming's Right-Hand Rule is suitable to find the direction of induced emf and hence the current when the conductor moves are at a right angle to a stationary magnetic field (as in an electric generator)

3.3 Fleming's Left-Hand Rule

Fleming's Left-Hand Rule is stated as follows:

"Stretch out the forefinger, middle finger and thumb of your left-hand so that they are at right angle to one another. If the forefinger points in the direction of magnetic field, the middle finger point in the direction of current, then the thumb will point in the direction of the force".



Fleming's left-hand rule is particularly suitable to find the direction of force on a current conductor when it is placed in a magnetic field (as in an electric motor).

3.4 Position of the loop & the voltage wave form for one cycle at 90^O intervals of rotation

An elementary revolving armature AC generator, otherwise commonly called an alternator, consists of a wire loop that can be rotated in a stationary magnetic field. This will produce an induced e m f in the loop. Sliding contacts (brushes and slip rings) connect the loop to an external circuit (Refer Figure 3.2). The pole pieces (marked N and S) provide the magnetic field. They are shaped and positioned to concentrate the magnetic field as close as possible to the wire loop. The loop of wire that rotates through the field is called the rotor. The ends of the rotor are connected to slip rings, which rotate with the rotor.

The stationary brushes, usually made of carbon, maintain contact with the revolving slip rings. Additives like graphite and copper may also be used, based upon the current-rating (or grade) of the brushes. The brushes are connected to the external circuit via copper conductors commonly known as pigtails.

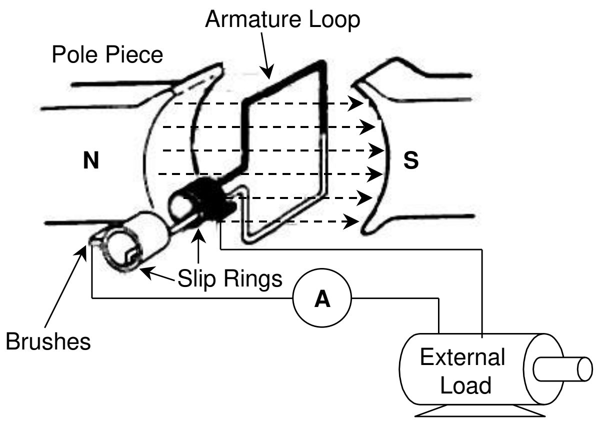


Figure 7.2 – The Elementary Alternator

The elementary generator produces a voltage in the following manner (Refer Figure 7.3). The rotor (or armature in this example) is rotated in a clockwise direction. Figure 7.3, position A shows its initial or starting position. This will be considered the 0^0 or initial position. At 0^0, the armature loop is perpendicular to the magnetic field. The black and white conductors of the loop are moving parallel to the field. At the instant when the conductors are moving parallel to the magnetic field, they do not cut any lines of force. There is no relative motion between the magnetic lines of force and the conductor when they move in the same direction. Thus, no electro motive force is induced in the conductors, and the meter in position A indicates ‘0’.

As the armature loop rotates from position A to B, the conductors cut through more and more lines of flux at a continually increasing angle. At 90^0 (B), they are cutting through a maximum number of magnetic lines of flux and at a maximum angle.

The result is that between 0 and 90^0, the induced e m f in the conductors builds up from 0 to a maximum value. Observe that from 0 to 90^0, the black conductor cuts down through the magnetic field (or flux). At the same time, the white conductor cuts up through the magnetic field. The induced e m f in the conductors is series-aiding. This means the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced voltages. The meter at position B reads maximum value.

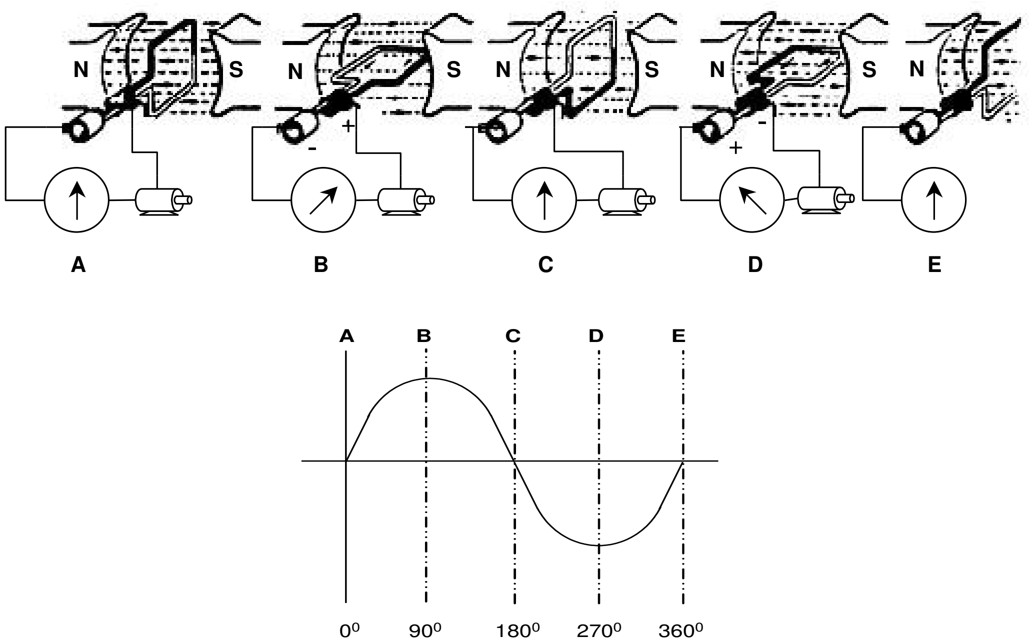


Figure 7.3 – The Elementary Generator's Sine Wave Output (Rotating Armature)

As the armature loop continues rotating from position B (90^0) to position C (180^0), the conductors that were cutting through a maximum number of lines of flux at position B now cut through fewer lines of flux. At C, they are again moving parallel to the magnetic field. They no longer cut through any lines of flux. As the armature rotates from 90 to 180^0, the induced voltage will decrease to 0 in the same manner as it increased from 0 to 90^0. The meter again reads 0. From 0 to 180^0, the conductors of the rotor armature loop have been moving in the same direction through the magnetic field.

Therefore, the polarity of the induced voltage has remained the same. This is shown by A through C on the graph. As the loop starts rotating beyond 180^0, from C through D to A, the direction of the cutting action of the conductors (of the loop) through the magnetic field reverses. Now the black conductor cuts up through the field.

The white conductor cuts down through the field. Thus, the polarity of the inducted voltage reverses. Following the sequence shown in C through D and back to A, the voltage will be in the direction opposite to that shown from positions A, B, and C.

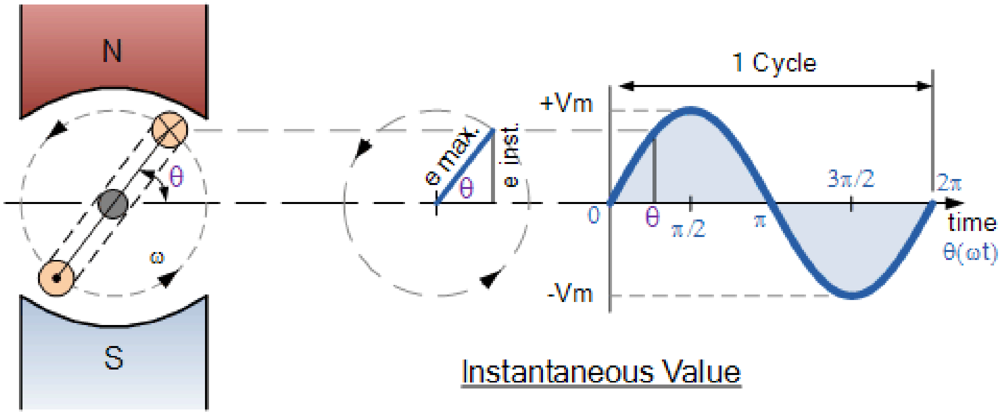
The terminal voltage will be the same as it was from A to C except for its reversed polarity, as shown by meter deflection in D. The graph in Figure 7.3 shows the voltage output wave form for the complete revolution of the loop and is sinusoidal in nature (a mathematical curve that describes a smooth repetitive oscillation). It has derived its name from the sine function of which it is the graph.

3.4.1 Relationship between instantaneous voltage, conductor velocity, the sine of the displaced angle

The EMF induced in the coil at any instant of time depends upon the rate or speed at which the coil cuts the lines of magnetic flux between the poles and this is dependant upon the angle of rotation, Theta (θ) of the generating device. Because an AC waveform is constantly changing its value or amplitude, the waveform at any instant in time will have a different value from its next instant in time.

For example, the value at 1ms will be different to the value at 1.2ms and so on. These values are known generally as the Instantaneous Values, or Vi Then the instantaneous value of the waveform and also its direction will vary according to the position of the coil within the magnetic field as shown below.

3.4.1.1 Displacement of a Coil within a Magnetic Field



The instantaneous values of a sinusoidal waveform are given as the "Instantaneous value = Maximum value x sin θ" and this is generalized by the formula: $\omega = 2\pi f$ *(rad/sec)*

Where, Vmax is the maximum voltage induced in the coil and $\theta = \omega t$, is the rotational angle of the coil with respect to time.

If we know the maximum or peak value of the waveform, by using the formula above the instantaneous values at various points along the waveform can be calculated. By plotting these values out onto graph paper, a sinusoidal waveform shape can be constructed.

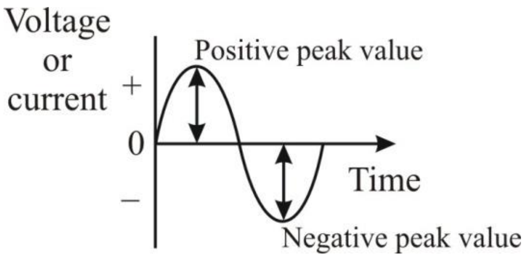
In order to keep things simple, we will plot the instantaneous values for the sinusoidal waveform at every 45^{O} of rotation giving us 8 points to plot. Again, to keep it simple we will assume a maximum voltage, V_{MAX} value of 100V. Plotting the instantaneous values at shorter intervals, for example at every 30^{O} (12 points) or 10^{O} (36 points) for example would result in a more accurate sinusoidal waveform construction.

3.5 Wave Form of an A.C. Voltage

The term AC or to give it its full description of Alternating Current, generally refers to a time-varying waveform with the most common of all being called a Sinusoid better known as a Sinusoidal Waveform.

Sinusoidal waveforms are more generally called by their short description as Sine Waves. Sine waves are by far one of the most important types of AC waveform used in electrical engineering.

The shape obtained by plotting the instantaneous ordinate values of either voltage or current against time is called an AC Waveform. An AC waveform is constantly changing its polarity every half cycle alternating between a positive maximum value and a negative maximum value respectively with regards to time with a common example of this being the domestic mains voltage supply we use in our homes.

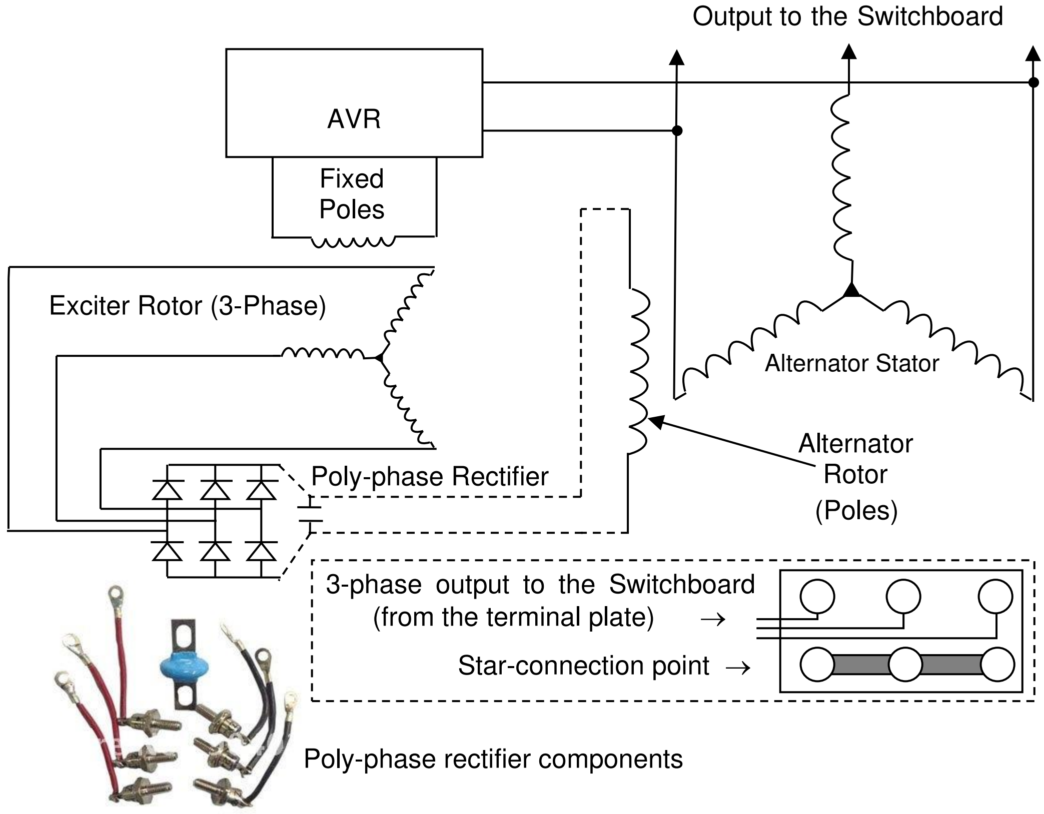


3.6 Peak Value

Definition: The maximum value attained by an alternating quantity during one cycle is called its Peak value. It is also known as the maximum value or amplitude or crest value.

$$V_P = \sqrt{2} \times V_{RMS} = 1.414\ V_{RMS}$$

3.7 A Simple Circuit for A Three-Phase Supply from An Alternator

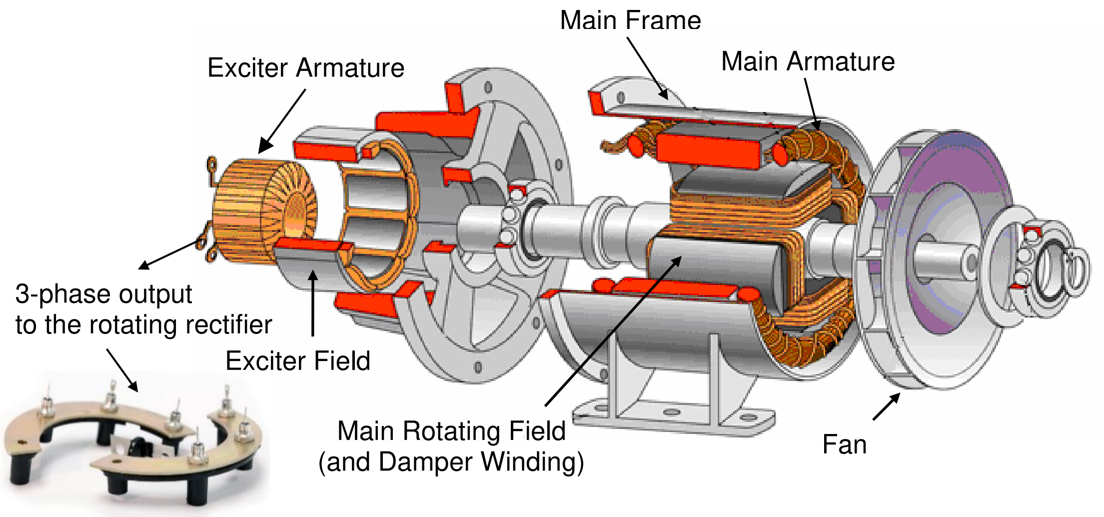


A Brushless Alternator Circuit

3.7.1 The Unique Features

In this machine, slip rings and brushes are eliminated and excitation is provided not by a conventional direct current exciter but by a small alternator within the set itself. There are no direct electrical connections between the rotating and stationary windings of the generator (Refer Figure 7.12).

The exciter has the unusual arrangement of three-phase output windings on the rotor and magnetic (field) poles fixed in the casing. The casing pole-coils are supplied with direct current from a static automatic voltage regulator. Three-phase current generated in the windings on the exciter's rotor passes through a 3-phase rectifier assembly on the shaft and then to the main alternator poles; no slip rings are needed.



Rotating Rectifier Image Courtesy: www.hipowersystems.com

Figure 7.13 – Exploded View of a Brushless Alternator

The major components are briefly explained below:

3.7.2 The Exciter

The exciter portion houses a mini generator that develops the power necessary to develop the magnetic field in the main generator portion. It consists of the following main components:

3.7.3 The Exciter Field

The exciter field is a stationary direct current-energized winding. This is the winding where the DC magnetic field is initially developed. Even before any voltage regulation takes place, a residual magnetic field* exists in the poles. During voltage regulation, DC in the exciter's field induces an e m f, resulting in current flow in its armature.

*** *Residual Magnetism***

(a) Now we know that residual magnetism exists in all ferrous metals that have had a current carried around it. In many generators, there is not enough material to provide a substantial residual magnetic field to use in creating an e m f. The ship's service generator has a lot of metal.

The material mass maintains adequate residual magnetism in the exciter's field that in turn helps to induce an e m f in the exciter's armature when there is motion. It will also be found that the properties of the metal involved will cater to a wider hysteresis loop or "B/H" curve.

(b) Residual magnetism in the generator's exciter field allows the generator to build up voltage while starting. This magnetism is sometimes lost due to shelf time or improper operation, among other reasons. Restoring this residual magnetism is possible and is sometimes referred to as 'flashing the exciter field'.

It is also possible that initially, self-excited ship service generators may need to have the fields flashed to establish the residual magnetism, which is necessary to start the exciter's induction process.

Note: *Read the manufacturer's recommendations carefully. Damage to the generator or voltage regulator will result if proper procedures are not correctly followed.*

To restore the small amount of residual magnetism necessary to begin a voltage build-up, connect a 12-volt battery to the exciter field while the generator is at rest. This is done as follows:

1. Remove the exciter field leads e.g., F+ and F- from the automatic voltage regulator.

CAUTION!

- ***Failure to remove the field leads from the regulator during flashing procedures may destroy the automatic voltage regulator.***

2. Measure the exciter field resistance across the F+ to the F- ends. You should be able to read some value of resistance as you are measuring a continuous winding. An infinite resistance reading would indicate an open circuit in the exciter field. Also ensure that there is no grounding in the circuit.
3. Connect F+ to the positive pole of the battery.
4. Hold the F- lead by the insulated portion of the lead wire, touch F- to the negative pole of the battery for about 5 to 10 seconds and then remove it.
5. Reconnect F+ and F- to the regulator.
6. Repeat the procedure if the generator fails to build voltage.

3.7.4 The Exciter Armature

The exciter armature is a three-conductor, three-phase rotating winding. The exciter armature is located directly inside a tubular stator. A three-phase e.m.f is induced in the exciter armature as it rotates inside the fixed magnetic field of the exciter. Together, the exciter's field and armature develop a three-phase AC output. In effect, this is a *rotating armature generator*. However, the frequency of its output is 3 to 10 times higher than the main armature's output frequency; this ensures higher stability and faster response to varying loads. This portion of the generator is used to provide the AC supply input to the rotating rectifier through co-axially mounted cables. Since current is induced into the armature without the aid of wires, brushes and slip rings are eliminated.

3.7.5 The Rotating Rectifier

In order to produce the enhanced three-phase output from the main armature of the generator (necessary for the large power requirements of the distribution system), the main field must be provided with a direct current source. To convert (or rectify) the exciter's output from AC to DC, the rotating rectifier is used. This rectifier provides the same conversion (from AC to DC) as is depicted in Figures 7.12 and 7.13.

3.7.6 Pilot Exciter

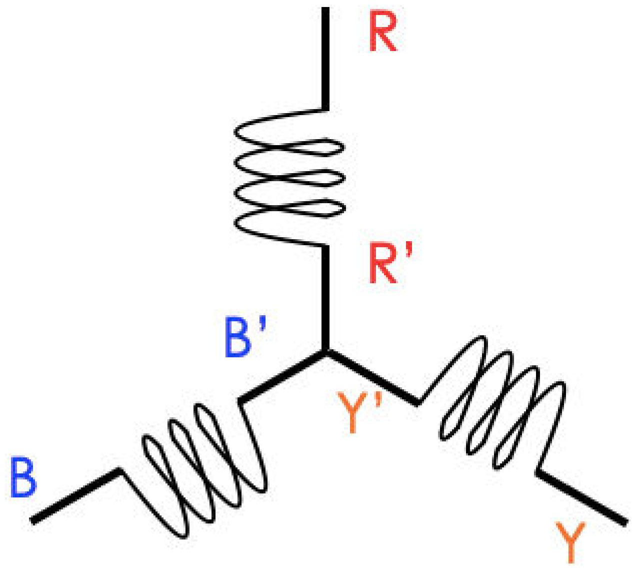
A pilot exciter is in a permanent magnet generator is a special set of magnets. The permanent magnet, also called a PMG (permanent magnet generator) mounted on the rotor shaft of the main generator. The armature winding of the PMG is a stationary part which is mounted on stator.

Thus, when the rotor rotates, the field flux created by the permanent magnet will also rotate and as the armature is stationary, there will be flux linkage in the armature winding of the PMG and an EMF will be induced across the terminals of the armature of the pilot exciter.

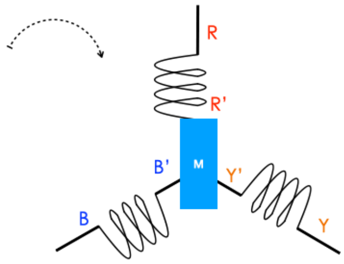
This armature thus produces three-phase ac power by using the mechanical energy of the rotor. This AC power from the pilot exciter is then rectified by a thyristor bridge. The DC is then feed to the field winding of the main exciter, which is wound on the stator of the main exciter.

Note that the permanent magnet of the pilot exciter is mounted on rotor, armature of pmg is stationary as it is wounded on stator and field winding of main exciter is stationary as it is also wounded to stator of main exciter. Normally pmg has 16 poles, so the ac produced by pmg will be at a frequency of 400 Hz ($f = PN/120$, $N = 3000$ rpm). Because of high frequency the ripple content in the rectified dc will be low. That is why pmg produces ac power at this higher frequency.

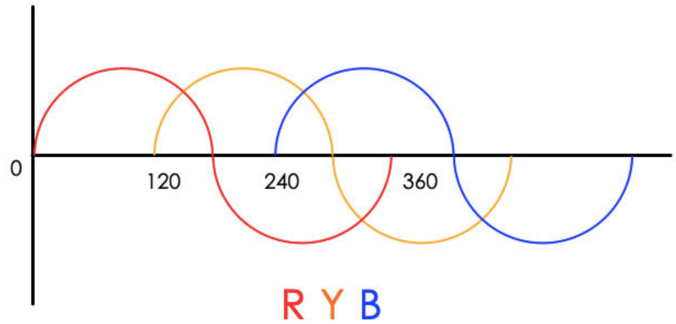
3.8 Phase Sequence of A 3-Phase Alternator



Consider a winding of a 3-phase alternator as shown in the above figure. We know that phase difference is 120^O in 3-phase system. Why 120^O? That because the windings are placed 120^O apart from each other. So, if you would like to have phase difference of 90^O, just place the windings 90^O apart from each other. It's all about how you place the windings.



Let's say the magnet is rotating in clockwise direction (as shown above), that means, winding Y will reach its peak value first, after that winding R and then winding B will have it's peak. As you might have guessed correctly, winding Y reached its peak value right after the magnet has rotated 120^{O} from its initial position. Similarly, when the magnet will rotate 240^{O} from its initial position, winding B will reach its peak value. We can also say that, waveform of winding Y is leading the waveform of winding B by an angle of 120^{O}, or we can say that waveform of winding Y is lagging the waveform of winding R by 120^{O}.



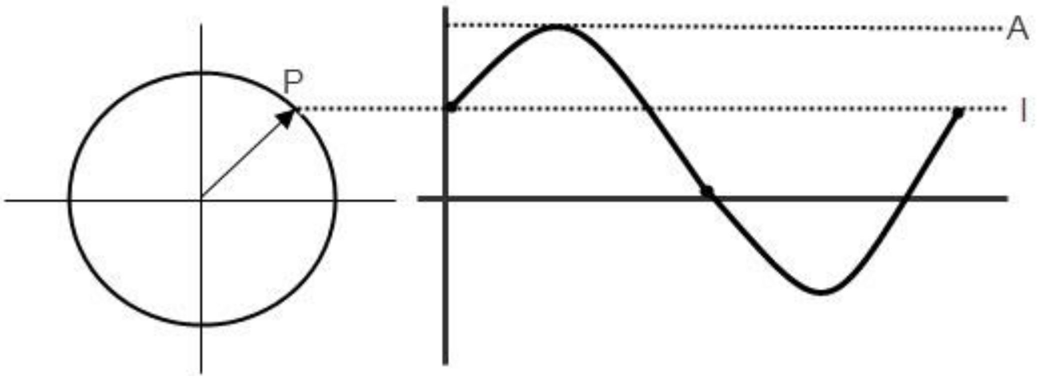
So, if you observe the sequence of reaching peak values, you'll find that winding R is reaching its peak value first, and then winding Y and then winding B. And this sequence will continue till the magnet is rotating in clockwise direction.

In polyphase system, the order in which voltage waveform reaches their respective peak values is called as phase sequence.

So, in this case our phase sequence would be **R-Y-B**. This is because, R phase reaches it's peak value first and then Y and then B. Phase sequence can sometimes also called as phase rotation. So, you need not to get confused between phase sequence and rotation as both are one and the same.

3.9 Complete Cycle of a Sine Wave by Vertical Components of a Rotating Vector

Every alternating wave has a positive half cycle and a negative half cycle in its complete cycle of revolution, along with the coordinate axis. Of course, the phasor also represents the wave properties in a coordinate plane only. The phase of the waveform for one complete revolution is 2π or 360^{O}. In a phasor diagram, we represent the instantaneous voltage (or amplitude) with a moving vector, as shown in figure below



In the above figure, the line A represents the maximum amplitude of the wave form and the line 'I' is the magnitude at the point P, of the phasor vector representation. The vector represents the values from 0^{O} to360^{O} in the axis, at different instances of time.

The vector represents both magnitude and the phase of the waveform. The magnitude is represented along the vertical axis and the phase of the waveform is represented along with the Horizontal axis. The phase of a waveform may be represented in either degrees or radians.

Basically, a rotating vector, simply called a "Phasor" is a scaled line whose length represents an AC quantity that has both magnitude ("peak amplitude") and direction ("phase") which is "frozen" at some point in time.

A phasor is a vector that has an arrow head at one end, which signifies partly the maximum value of the vector quantity (V or I) and partly the end of the vector that rotates.

Generally, vectors are assumed to pivot at one end around a fixed zero point known as the "point of origin" while the arrowed-end representing the quantity, freely rotates in an anti-clockwise direction at an angular velocity, (ω) of one full revolution for every cycle.

This anti-clockwise rotation of the vector is considered to be a positive rotation. Likewise, a clockwise rotation is considered to be a negative rotation. Although both the terms “vectors” and “phasors” are used to describe a rotating line that itself has both magnitude and direction, the main difference between the two is that a vectors magnitude is the “peak value” of the sinusoid while a phasor’s magnitude is the “rms value” of the sinusoid. In both cases the phase angle and direction remain the same.

The phase of an alternating quantity at any instant in time can be represented by a phasor diagram, so phasor diagrams can be thought of as “functions of time”. A complete sine wave can be constructed by a single vector rotating at an angular velocity of $\omega = 2\pi f$, where f is the frequency of the waveform. Then a phasor is a quantity that has both “Magnitude” and “Direction”.

Generally, when constructing a phasor diagram, the angular velocity of a sine wave is always assumed to be: ω in radians per second. Consider the phasor diagram below:

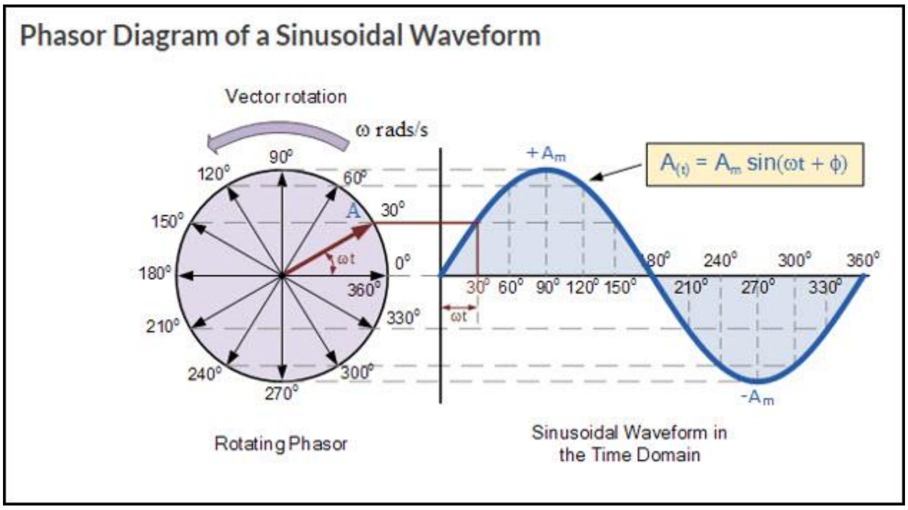
using a triangle produced from the above objective, confirms that

$$\underline{e} = \sin\theta E_{max}$$

3.10 Degrees and Radians Superimposed on The Wave Sine

In AC circuits, angles are frequently measured in radians, rather than degrees. Radian is defined by an arc of a circle where the length of an arc is equal to the radius of the circle. The circumference of a circle equals $2\pi r$ where r is the radius. A complete circle will therefore have 2π radians, which is subtended by 360°. In other words, to calculate how many degrees are in a radian, you can state the number of radians in the circle as 2π radians, which is equal to the number of degrees in a circle (360°). So, the number of degrees in a radian can be found by dividing 360° by 2π.

Formula: $2\pi r = 360°$, $r = 360°/2\pi$, 1 radian = 57.3°



3.11 Angular Velocity

Angular Velocity is another term that's related to a radian measure. It is the time rate of change in angular displacement. This is equal to the distance traveled by the conductor, which is measured in radians, divided by the period (T), time taken for one revolution. The term angular velocity can also be stated with a letter symbol ω, which is the lowercase Greek letter Omega (ω). Therefore, ω is equal to so many radians per second. If we look at just one waveform, then ω is equal to 2π radians over time in seconds i.e. ($\omega = 2\pi/T$). The angle through which the conductors move in one second may be written as:

Angular velocity = $\omega = 2\pi/T$ (radians/second)

Another term we will discuss that relates to the radian measure and angular velocity is frequency. Frequency (f) refers to the number of cycles or waveforms per second with unit of hertz or Hz. In formula, $f = 1/T$. If we combine the formulas of the last two terms, we arrive at angular velocity or Omega equal to 2πf.

Given: $\omega = 2\pi/T$ and $f = 1/T$, therefore $T = 1/f$, combined $\omega = 2\pi/(1/f) = 2\pi f$

The term omega ω is a term that you will encounter in a number of formulas as you study AC theory in electricity and electronics.

3.12 Calculating the Instantaneous Voltage, Given the Unknown

Q. 220 V, 50 Hz, ac is applied to a resistor. The instantaneous value of voltage is

$V = Vm \sin \omega t$

$V = Vm \sin\theta$

$Vm = Vrms \times \sqrt{2}$

$= 220 \times \sqrt{2}$ V ω

$= 2\pi f = 2\pi \times 50 = 100\pi$

$\therefore V = 220\sqrt{2} \sin 100\pi t$

3.13 e = Blv to produce; e = E_{max} sinθ, where e is the instantaneous voltage, E_{max}, is the maximum voltage and θ is the displaced angle

The EMF induced in a straight conductor of length *l* moving with velocity v perpendicular to a magnetic field B is $E = Blv$

Where:

B, *l* and v are mutually perpendicular. The emf is in volts when B is in webers per m^2, *l* is in meters, and v is in m/sec.

If the velocity vector **v** makes an angle θ with the direction of the magnetic field,

$E = Blv \sin\theta$

3.14 Factors Affecting the Induced Voltage

The common factors are:

- the flux density "B"
- the number of turns in the coil "N"
- the conductor's / flux cutting rate "v"
- the active length "l"

Faraday's experiments showed that the EMF induced by a change in magnetic flux depends on only a few factors. First, EMF is directly proportional to the change in flux Δ. Second, EMF is greatest when the change in time Δt is smallest—that is, EMF is inversely proportional to Δt.

Finally, if a coil has N turns, an EMF will be produced that is N times greater than for a single coil, so that EMF is directly proportional to N.

3.14.1 The E M F Equation

The magnitude of the induced voltage depends on the strength of the magnetic field, rate of cutting and length of the conductor. To substantiate this statement, the e m f equation is as follows:

$e = 2NBlv \sin \theta$ *volts*

Where; *e* is the e m f generated as mentioned,

2 – since each coil has 2 sides,

N is the number of turns (conductors)

B is the flux density in wb/m^2

l is the *active* length of the conductor (i.e., the length beneath the poles)

v is the peripheral velocity in metres / second

Sin θ – when the coil side (conductor) has turned through an angle θ, only Sinθ is effective since it is perpendicular to the direction of both the magnetic flux and the conductor in reckoning.
The Cos θ component is ignored as it is found to be a parallel one and hence ineffective.

Now when *e* is at its maximum, the angle θ = 90^0 and as we know that Sin90 = 1, we can re-write the equation as Em = 2BN*lv* volts.

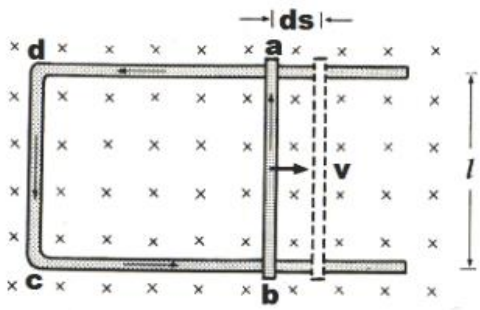
If *b* is the width of the coil in metres, *f* the frequency of rotation in hertz, then, the *peripheral velocity v = Π.b.f*

So, Em = 2BN*lΠ.b.f* volts (knowing that *l* is the *active* length and *b* is the breadth, then the area of the coil in square metres can be represented by *A)*

∴ Em = 2*Π.fNBA* volts

By definition, E = dW/dq. That is, the emf is the work done on the circulating charge per unit charge (coulomb) displaced past a point of the circuit. Let us consider the figure below in which a moving conductor ab of length *l* slides along a stationary U-shaped conductor, where the loop is in a plane perpendicular to a magnetic field B. If conductor ab moves to the right at a velocity v, a current I will flow in the loop adcb. Remembering that a magnetic field exerts a force of F = BI*l* newtons on a long, straight current-carrying conductor perpendicular to the field, we note that the current I moving through the moving conductor ab will cause a side-thrust to the left on ab with a force of F = BI*l* newtons.

Because of this side-thrust, an external force provided by some working agent is required to maintain the motion. The work done by this agent is the work done on the circulating charge. There is a direct conversion here of mechanical energy to electrical energy.



The distance moved in time t is

ds = vdt

and the work done is

dW = Fds = *l*IB·vdt

Now the product of I and dt is the charge dq displaced in this time, so

dW = Blvdq

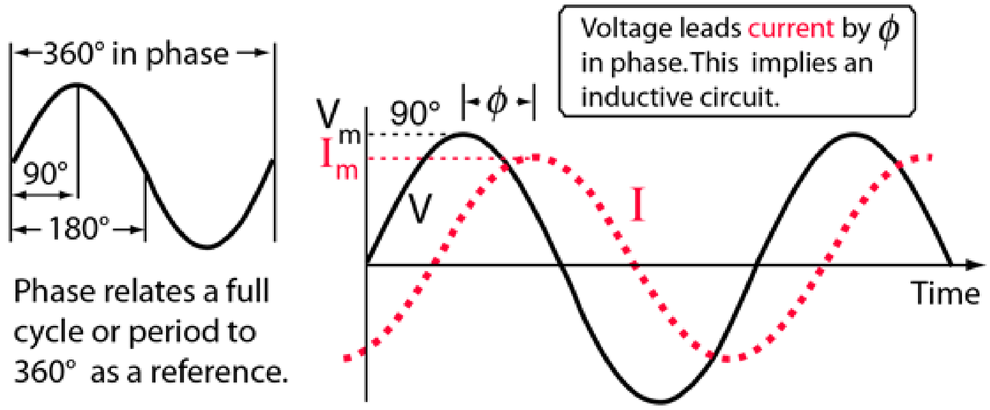
or

dW/dq = Blv

Since E = dW/dq, E = Blv

3.15 Phase Difference Between Voltage and Current

When capacitors or inductors are involved in an AC circuit, the current and voltage do not peak at the same time. The fraction of a period difference between the peaks expressed in degrees is said to be the phase difference. The phase difference is $\leq 90^{O}$. It is customary to use the angle by which the voltage leads the current. This leads to a positive phase for inductive circuits since current lags the voltage in an inductive circuit. The phase is negative for a capacitive circuit since the current leads the voltage. The useful mnemonic ELI the ICE man helps to remember the sign of the phase. The phase relation is often depicted graphically in a phasor diagram.



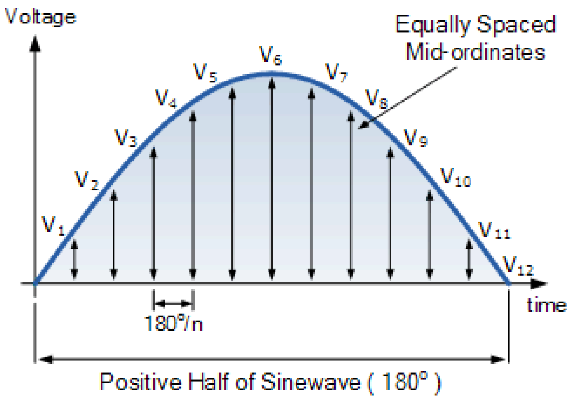
3.16 Use of Root Mean Square (r.m.s.) Values

This **RMS** is a mathematical quantity (used in many *math* fields) used to compare both alternating and direct currents (or voltage). In other words (as an example), the RMS value of AC (current) is the direct current which when passed through a resistor for a given period of time *would* produce the same heat as that produced by alternating current when passed through the same resistor for the same time.

Practically, we use the RMS value for all kinds of AC appliances. *The same* is applicable to alternating voltage also. We're taking the RMS because AC is a variable quantity (consecutive positives and negatives). Hence, we require a mean value of their squares thereby taking the square root of sum of their squares.

Another simple way to look at it, geometrically, is that by squaring V, in effect you flip the negative voltage to positive ($(-V)^2 = V^2$), then find the average magnitude of these square values. By taking the square root, you get back to an unsquared value that averages the magnitudes, regardless of sign.

3.16.1 RMS Value for Given Values of Instantaneous Voltage or Current for a Half Cycle



Each mid-ordinate value of a waveform (the voltage waveform in this case) is multiplied by itself (squared) and added to the next. This method gives us the “square” or Squared part of the RMS voltage expression. Next this squared value is divided by the number of mid-ordinates used to give us the Mean part of the RMS voltage expression, and in our simple example above the number of mid-ordinates used was twelve (12). Finally, the square root of the previous result is found to give us the Root part of the RMS voltage.

Then we can define the term used to describe an rms voltage (V_{RMS}) as being "the square root of the mean of the square of the mid-ordinates of the voltage waveform" and this is given as:

$$V_{RMS} = \sqrt{\frac{\text{Sum of mid-ordinate (voltages)}^2}{\text{Number of mid-ordinates}}}$$

and for our simple example above, the RMS voltage will be calculated as:

$$V_{RMS} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + V_4^2 .... + V_{12}^2 + V_{12}^2}{12}}$$

So, lets assume that an alternating voltage has a peak voltage (V_{pk}) of 20 volts and by taking 10 mid-ordinate values is found to vary over one half cycle as follows:

Voltage	6.2V	11.8V	16.2V	19.0V	20.0V	19.0V	16.2V	11.8V	6.2V	0V
Angle	18°	36°	54°	72°	90°	108°	126°	144°	162°	180°

$$V_{RMS} = \sqrt{\frac{6.2^2 + 11.8^2 + 16.2^2 + 19.0^2 + 20.0^2 + 19.0^2 + 16.2^2 + 11.8^2 + 6.2^2 + 0^2}{10}}$$

$$V_{RMS} = \sqrt{\frac{2000}{10}} \quad = \quad V_{RMS} = \sqrt{200} \quad = 14.14 \text{ Volts}$$

Then the RMS Voltage value using the graphical method is given as: 14.14 Volts.

The RMS value for a sine wave is 0.707 of the peak value

3.17 RMS Voltage Analytical Method

The graphical method above is a very good way of finding the effective or RMS voltage, (or current) of an alternating waveform that is not symmetrical or sinusoidal in nature. In other words the waveform shape resembles that of a complex waveform. However, when dealing with pure sinusoidal waveforms we can make life a little bit easier for ourselves by using an analytical or mathematical way of finding the RMS value.

A periodic sinusoidal voltage is constant and can be defined as $V_{(t)} = V_{max}*\cos(\omega t)$ with a period of T. Then we can calculate the **root-mean-square** (rms) value of a sinusoidal voltage ($V_{(t)}$) as:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V_m^2 \cos^2(\omega t)\, dt}$$

Integrating through with limits taken from 0 to 360° or "T", the period gives:

$$V_{RMS} = \sqrt{\frac{V_m^2}{2T}\left[t + \frac{1}{2\omega}\sin(2\omega t)\right]_0^T}$$

Where: Vm is the peak or maximum value of the waveform. Dividing through further as $\omega = 2\pi/T$, the complex equation above eventually reduces down too:

RMS Voltage Equation

$$V_{RMS} = V_{pk}\frac{1}{\sqrt{2}} = V_{pk} \times 0.7071$$

3.18 Principles of Electromagnetic Induction and its Main Applications

Electromagnetic induction is the production of electromotive force otherwise known as voltage across an electrical conductor where the magnetic field changes. For the discovery of induction, Micheal Faraday was awarded this credit in 1831. Here, the Faraday's law of induction was described by Maxwell in mathematical terms.

Take for example any conductor and place it in a specific position. Here the process of electromagnetic induction will let the conductor vary keeping the magnetic field stationary.

Now, there is a simple question to ask. Without touching another circuit, how is current induced by another circuit? Further, what does any of this have to do with magnetism? Before learning about that, we need to look at a few principles linking electricity and magnetism:

1. The magnetic field surrounds every electric current.
2. Fluctuating magnetic fields created around alternating currents.
3. Faraday's Law states that the magnetic field causes the flow of the current in conductors that are placed within them.

3.18.1 Principle of Electromagnetic Induction

When we combine these above mentioned three principles, it means that a changing electric current is surrounded by a related changing magnetic field, which will, in turn, generate an electrical current in a conductor placed within it, having its magnetic field. It is the electromagnetic likeness of nesting Matryoshka dolls. The first current generated the second current in electromagnetic induction when a current flows through a conductor placed in a magnetic field.

When it comes to the principle of electromagnetic induction, it will enable the transformers, motors, electric generators and other rechargeable items such as wireless communication devices or electric toothbrushes to adopt the principle. Apart from that, your rice cooker works on using induction. Now let's learn how induction cooktops are heated by using induced current.

3.18.1.1 Applications

- Current clampmeter.
- Electric generators.
- Electromagnets
- Hall effect meters.
- Induction cooking.
- Induction motors.
- Induction sealing

3.18.2 Faraday's Law of Electromagnetic Induction

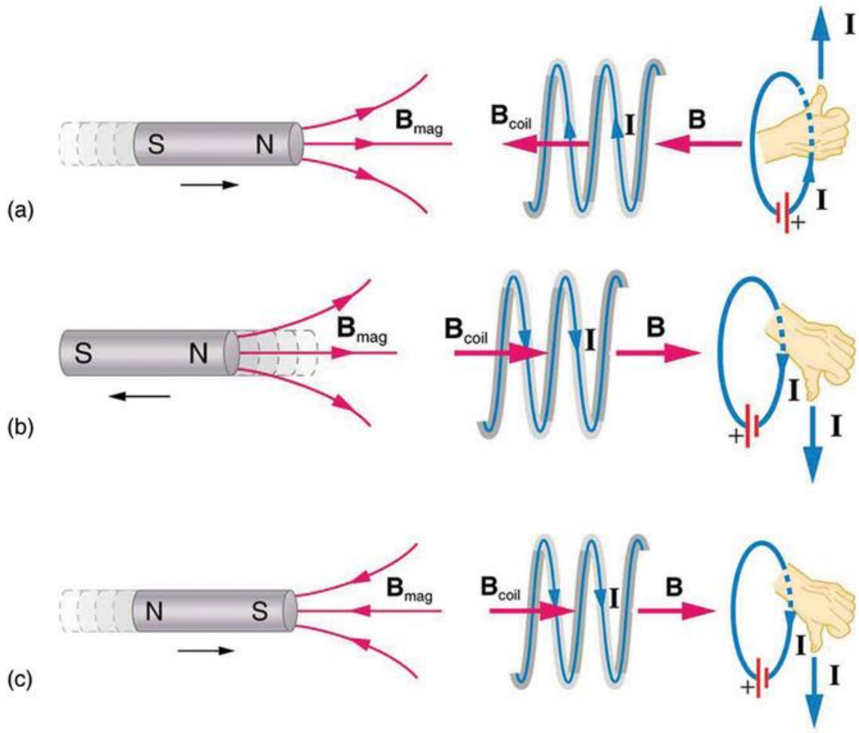
Faraday's law of electromagnetic induction, also known as Faraday's law, is the basic law of electromagnetism which helps us to predict how a magnetic field would interact with an electric circuit to produce an electromotive force (EMF). This phenomenon is known as electromagnetic induction.

3.19 Lenz's law

The minus sign in Faraday's law of induction is very important. The minus means that the EMF creates a current I and magnetic field B that oppose the change in flux Δ; this is known as Lenz' law.

The direction (given by the minus sign) of the EMF is so important that it is called Lenz' law after the Russian Heinrich Lenz (1804–1865), who, like Faraday and Henry, independently investigated aspects of induction. Faraday was aware of the direction, but Lenz stated it, so he is credited for its discovery.

When this bar magnet is thrust into the coil, the strength of the magnetic field increases in the coil. The current induced in the coil creates another field, in the opposite direction of the bar magnet's to oppose the increase. This is one aspect of Lenz's law - induction opposes any change in flux. (b) and (c) are two other situations. Verify for yourself that the direction of the induced B coil shown indeed opposes the change in flux and that the current direction shown is consistent with the right hand rule.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Chapter 3

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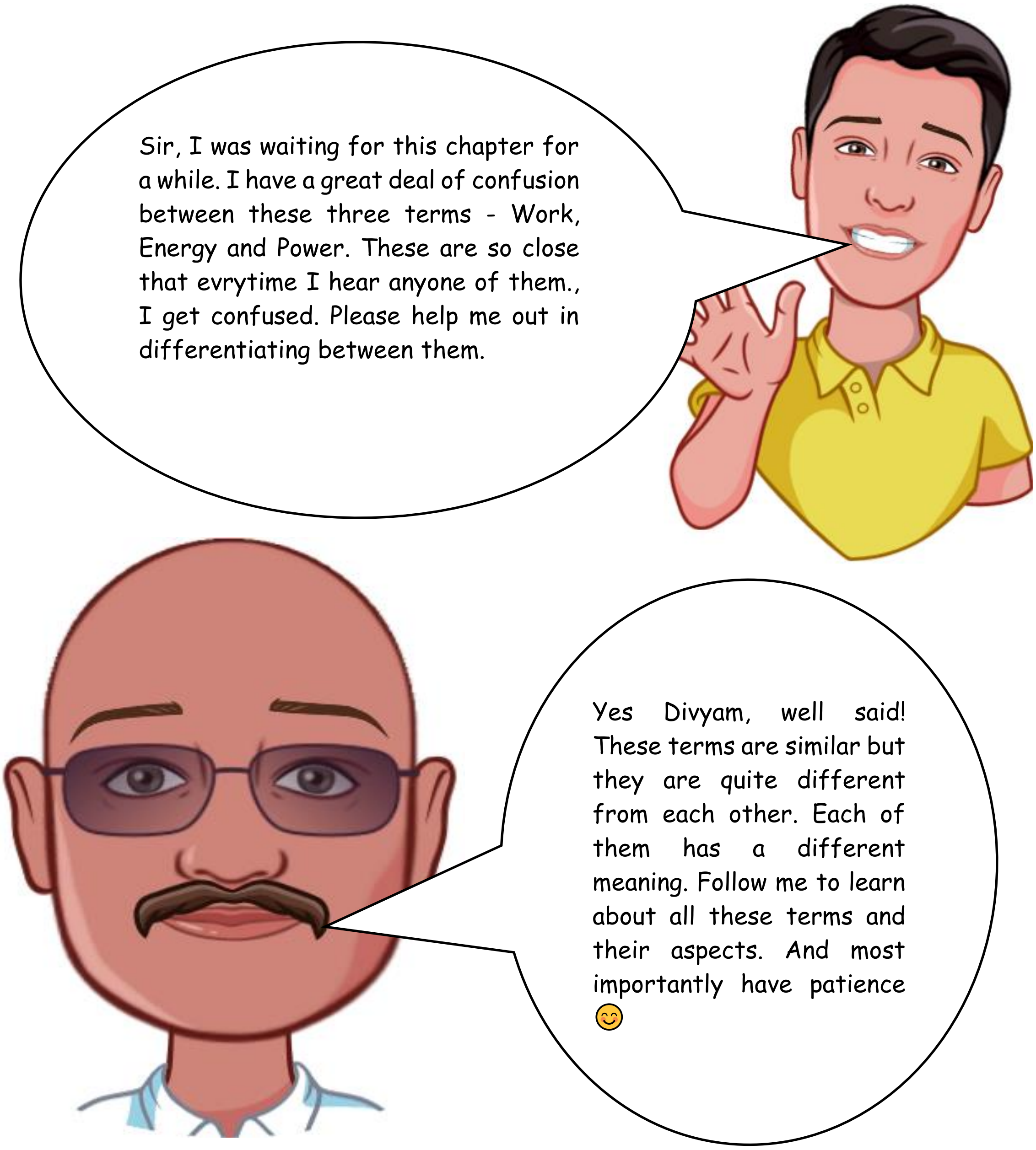
Chapter 4
Work, Power and Energy



Chapter 4

4.1 Introduction

Work, energy and power are the commonly used terms in electricity. They are probably the first thing you learn in your electrical class. Work and energy can be considered as two sides of the same coin. In this article, we will learn all about the concept of work, power and energy.

Work done is generally referred in relation to the force applied while energy is used in reference to other factors such as heat. Power is defined as work done per unit time.

4.2 Work

Definition: Work is said to be done when a force applied to an object, moves that object.

Formula: We can calculate work by multiplying the force by the distance of movement of the object.

$$W = F \times d$$

Unit: The SI unit of work is the joule (J)

4.3 Electrical Power

Definition: It is the rate at which work is done or energy is transformed in an electrical circuit. Simply put, it is a measure of how much energy is used in a span of time.

In physics, the rate of transfer of electrical energy by an electrical circuit per unit time is called electrical power. Here electrical energy can be either kinetic energy or potential energy. In most of the cases, potential energy is considered, which is the energy stored due to the relative positions of charged particles or electric fields. Electrical power is denoted by P and measured using Watt.

$P = V*I$

Where:

V is the potential difference (volts)

I is the electric current (Ampere)

The unit of power is watt (W).

4.4 Electrical Energy

First of all, we know that energy cannot be created or destroyed; it only changes state.

Definition of Electrical Energy: It is the ability of an electrical circuit to produce work by creating an action. This action can take many forms, such as thermal, electromagnetic, mechanical, electrical, etc. *Electrical energy* can be both created from batteries, generators, dynamos, and photovoltaics, etc. or stored for future use using fuel cells, batteries, capacitors or magnetic fields, etc. Thus, electrical energy can be either created or stored.

Formula: Electrical power * Time

Unit: Watt – hour (Wh) (the convenient unit is the kilowatthour kWh)

Difference is Between Electrical Energy and Power

- The energy which is said to be the electrical energy defines the energy which is generated due to the movement of a charge that is carried in a conductor.
- While we can again say or consider here that the electrical power specifies the rate of consumption of electrical energy by a device.
- The SI unit which is of electrical energy is said to be Joules. But the power which is electrical in nature, is measured in Watts or even kWh.

4.5 Work = Current × Time × Voltage

Joule per coulomb is emf (E) for the whole circuit.

Current (I) is coulomb per second at cross section.

So, power (P) of the whole circuit will be

P (power in watt) = E (emf in volt) × I (current in ampere)

Now, if V is the voltage drop or voltage difference in any particular part of this circuit and because current is same for whole circuit as well as to this part of the circuit, so power of this part of the circuit will be:

V (in volt) × I (current in ampere)

Electrical work done is equal to the energy so,

Energy of the whole circuit = E × I × t (watt hours)

Energy of the particular part of the circuit =V × I × t (watt hours)

Where t is time in hours

4.6 Simple calculations to determine energy and work

Electrical energy is the product of power multiplied by the length of time it was consumed. So, if we know how much power, in Watts is being consumed and the time, in seconds for which it is used, we can find the total energy used in watt-seconds. In other words, Energy = power x time and Power = voltage x current.

Problem 1: Work done by a battery (W = QV)

Work is a measure of energy in joules (J).

When we play with batteries we usually talk about electrical potential (V) and current (I).

To get work done by a battery, you need to know the total charge used (Q) used and the voltage (V), and plug it into W = QV to get work.

Since we usually talk about amps or current when dealing with batteries and not charge, we have to convert current into charge.

To do this, we need to know for how long (time t) the battery was delivering current.

Say, a 12-V battery delivered 10 amperes of current for 10 seconds.

Since A = C/t by definition, to get coulombs of charge you can multiple amperes by time in seconds.

Q = I * t = 10 A * 10 s = 100 C

W = Q * V =100 C * 12 V = 1200 J

Because power in watts is J/s to can calculate work from that as well if you know the time.

P = I * V = 10 A * 12 V = 120 Watts (J/s)

W = P * t = 120 J/s * 10 s = 1200 J

When we work with batteries, we usually deal with ampere-hours (Ah) when we talk about capacity. 1 Ah is 3600 Coulombs, so if our example battery has a capacity of 10 Ah we can calculate the work its capable of.

W = (10 Ah * 3600 C/Ah) * 12 V = 432000 J of electrical potential energy.

Because the voltage of batteries varies with the state of charge and the specific load on the battery, we use Ah to give the capacity, and not joules.

Problem 2: Calculate the electrical energy consumed by a 1200 W toaster in 30 minutes. What will be the cost of using the same for 1 month if 1 unit of electricity cost Rs. 4.

Hint: The electric energy consumed by an appliance is equal to the product of the power consumed by the toaster and time duration for which the toaster remains on. 1 unit of energy is equivalent to 1 kW consumed in 1 hour.

Formula Used:

Power = $\frac{Energy\ Used}{Time}$

Since, we been given the power used and time duration, we can calculate the energy utilized by the toaster as

Energy used = Power × Time

Since the toaster consumes 1200 W toaster in 30 minutes or 0.5 hour, we can calculate the energy

used by the toaster as

Energy used = 1200 × 0.5

Energy used = 600 Wh

Hence the energy used is,

Energy used = 0.6 kWh

The energy used by this toaster in 30 days will be

Energy Used = 0.6 × 30

Energy Used = 18 kWh

Since 1 unit of energy is equivalent to, and one unit of energy costs Rs. 4, the cost of 18 units will be:

Cost = 18 × 4

Cost = Rs. 72

Hence it will cost Rs. 72 to run a toaster half an hour daily for one month.

***Note**: We must note that an actual toaster might use different amounts of energy depending on the kind of mode of the toaster as well as depending on the amount of time it is used in a real-life scenario. We must also remember that 1 unit of energy is equivalent to using 1 kW of power in 1 hour and we can use this relation to determine the number of units required to power an appliance. 'Units' is the unit used by power companies to measure the consumption of electricity (kWh).*

Problem 3: A 220 V – 5 A electric lamp is used for 30 minutes. How much energy does it consume?

Solution:

Voltage (V) = 220 Volt

Electric current (I) = 5 Ampere

Time (t) = 30 minutes

= 30 x 60 seconds

= 1800 seconds

Electric power (P):

P = V I

= (220 Volt) (5 Ampere)

= 1100 Volt Ampere

= 1100 Watt

= 1100 Joule/second

Electric energy = Electric power x time

= (1100 Joule/second) (1800 second)

Electric energy = 1,980,000 Joule

= 1,980 kilojoule

Problem 4: A 220 V – 60 W soldering iron is used for 4 minutes. How much energy does it consume?

Known:

Power (P) = 60 Watt = 60 Joule/second

Voltage (V) = 220 Volt

Time (t) = 4 minutes = 4 x 60 seconds = 240 seconds

Wanted: Electric power

Solution:

220 Volt – 60 Watt means the electric solder works well if the potential difference or voltage is 220 volts and has a power of 60 Watt = 60 Joule/second, means that electric solder using the energy of 60 Joules per second.

Electric energy = electric power x time interval = (60 Joule/second) (240 second) = 14,400 Joule.

4.7 The Definition of Power, giving the units and symbols used; from the above objective, derive the expression Power = Voltage × Current (P = VI), giving the units used

If we look around ourselves, we'll find several things that require power to run or work. This power can be anything either in the form of electricity, physical, human resources, etc. The main agenda remains the same which is the ability to do work at a particular time.

The power formula can be defined as the work done by any specific object or source per given time.

Let's suppose A and B are two people doing the same task but A finished the task before B then what does it mean?

It simply means that A is more efficient than B and the efficiency is directly proportional to Power hence we can say that A is more powerful than B. This is exactly what power is, it is defined as the work done by a body in the given time.

Power = Work done by the object or body / Total time taken.

The Power formula differs as per the required statements, for example, it can be different for force related objects and also can differ for electronic devices.

Power Formulae - Electrical Power Formula Derivations and Examples

The Power Formula for Different Relations and Units are:

P = VI:

According to Ohm's law at a constant temperature, the current flowing through a conductor will be directly proportional to the potential difference between the ends of the conductor. It is also inversely proportional to the resistance offered by the conductor. We can define the electrical power in a circuit as the amount of energy produced or absorbed in a circuit.

Ohm’s law gives that,

$I = \frac{V}{R}$

Where:

I stands for the current in a circuit, V stands for the potential difference across the conductor, R stands for the resistance offered by the conductor

$P = \frac{W}{t}$

Where, P stands for the power, W stands for the work done and, t stands for the time.

From ohms’ law we know that,

$I = \frac{V}{R}$

The definition of power says that it is the amount of electrical energy produced or consumed by acircuit. Also, in other words we can say that the power in a circuit is the amount of work done by the circuit in unit time. It can be written as,

$P = \frac{W}{t}$ …equation (A)

By the definition of potential difference, we know that potential difference is the work done in bringing a charge from infinity to a particular point, we can write it as

$V = \frac{w}{Q}$

Where, V stands for the potential difference, w stands for the work done and Q stands for the total charge

From the above equation, we get

w = VQ

Substituting this expression of in equation (A), we get

$P = \frac{VQ}{t}$ … equation (B)

Now, we know that by definition the current is defined as the charge flowing through a conductor per unit of time. That can be written as,

$I = \frac{Q}{t}$

Substituting this value of current in equation (B), we get

P = V * I (Hence Proved)

This states that power is directly proportional to the potential difference of the conductor. Here P stands for power, V stands for potential difference and I stand for Current. The SI unit is the watt. The unit of V is in volt and for I it's in the column.

4.7.1 Electric Power Formula

$P = R \times 1^2$ or V^2/R: These formulas are a variant of ohm's law. Here R stands for resistance V stands for potential difference and I stand for current.

It states that power is directly proportional to the square of potential difference and inversely proportional to the resistance offered by the conductor.

4.7.2 The Power Equation

P = E/t: This formula is also called the mechanical power equation. Here E stands for energy in joule and t stands for time in seconds.

This formula states that the consumption of energy per unit of time is called power.

This is the most common and basic formula of power. This formula is derived from the work-energy theorem. It states that the work done per unit time is called power. Here W stands for work in joule and t stands for time in seconds.

P = F x s/t:

In this formula, F denotes force applied in the object, s denotes displacement of the object and t denotes the total time taken.

It states that the total time taken by an object to displace from one place to another when an external force is applied to it is called power.

The formula of power is different for different fields as mentioned above, but its meaning remains almost the same for all.

Using the equations from above objectives, derive $P = I^2 R$ and $P = \frac{V^2}{R}$

Derivation of some power formulae are as below:

Electric Power:

As we know for Ohm's law

V = I * R

I = V/R

Now putting this value in a standard equation, P = V*I

We get,

P = I * I * R

$P = I^2 * R$

Or

P = V * V/R

P = $\frac{V^2}{R}$ (Hence Proved)

Here,

P = Power of the object or body.

V = Potential Difference between two ends of a conductor.

I = current flowing through the circuit.

R = Resistance offered by the wire.

Power Formula:

p = F x s/t

As we know,

Power = Work done upon time

p = w/t

Work = Force(F)*Displacement(s) p = F x s/t

Here,

P = Power.

F = Force applied on the body.

W = Work done by the body.

t = Total time taken.

S = Total displacement of the body

Sources

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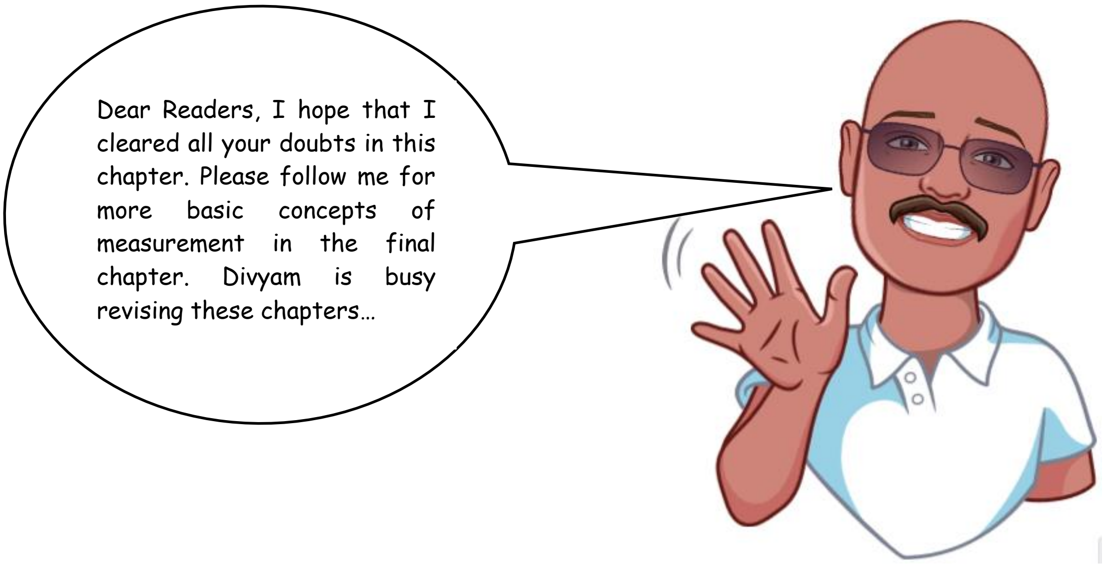


Chapter 5
Basic Measuring Instruments

5.1 Fundamentals of Test Equipment

5.1.1 Multi-meters

Routine electrical test work involves measuring current, voltage and resistance i.e. Amps, Volts and Ohms. This is most conveniently done using a multi-meter with all the necessary functions and ranges. The instrument may be the traditional switched-range analogue type (pointer and scale) or the more common digital type with auto-ranging and numerical display.

Instrument battery failure is checked when the instrument is set to read "Ω" with the probe tips connected together. If the pointer fails to indicate "0 **Ω"** after adjustment of the resistance range trimmer, the battery must be replaced. The instrument should be *switched-off* when it is not in use in order to preserve battery life.

If the multi-meter is a digital type, use the following steps to verify if the meter is safe to use:

a) Switch it on and connect the two probe tips together.

b) Set the selector switch to "DC V" (highest range). The display should indicate zero (0).

c) Repeat this for all "DC V" selector switch positions and note the *shift* of the decimal point.

d) Separate the probe tips.

e) Set the selector switch to **"Ω"** (highest range). The display should indicate "OL" (over-range) or "1" (depending upon the model).

f) Connect the probe tips together. The display should indicate zero (0).

g) Repeat this for all **"Ω"** selector switch positions and note the movement of the decimal point.

h) Set the selector switch to "AC V" (highest range).

i) Connect the probes to a suitable known live ac supply.

j) The display should indicate the correct voltage.

k) Similarly test the dc voltage range with a known dc source and note the polarity indication on the meter.

l) The instrument's battery failure is usually indicated by the numeric display. The display may include "BT" or the decimal point may *blink,* or some other display effect may be evident like random numbers appearing when we use it.

m) The instrument should be switched off when it is not in use, to preserve battery life.

The following simple proving tests should be performed every time, before using the instrument. It is obviously very dangerous to touch conductors believing them to be dead, having checked them with a faulty instrument or adopting the wrong procedures.

5.1.2 Voltage Measurement

- ✓ Prove the correct operation of the instrument
- ✓ Switch the instrument to the *highest* voltage range (either ac V or dc V as appropriate)
- ✓ Connect the probes to the terminals being tested.

Take great care not to touch the probe tips; remember that the equipment being tested is live.

- ✓ Note down the voltage reading. If a *lower* voltage range would give a more accurate reading, adjust the selector switches accordingly to shift the decimal point. However, most digital meters have an auto-ranging facility.
- ✓ No harm will be caused to the instrument by operating the selector range switches while they are still connected to a live supply.
- ✓ Great care must be taken to avoid switching into either the *current* or *resistance* modes. This would almost certainly operate the instrument overload device and may cause severe damage to the instrument and danger to you. Take time to operate the selector switches during the operation and think carefully.
- ✓ Disconnect the probes and switch the instrument Off.

5.1.3 Current Measurement

Most test instruments can only measure up to a few amps DC (usually a maximum of 10 **A)**. The current measuring facility is intended only for low-current components, and in particular, for electronic circuits. The instrument will almost certainly be damaged if it is used to measure the current to motors and other power circuits.

The basic current range can be extended by using external shunts (for d.c.) and current transformers (for a.c.). These accessories are generally purchased separately from the instrument manufacturers.

The procedure to be used to measure current in a low-current circuit – generally up to 200 mA:

- ✓ Prove that the instrument is operating satisfactorily.
- ✓ Switch the instrument to the highest range (either ac A – only if available or dc A as appropriate).
- ✓ Turn Off the power to the circuit to be tested and discharge all capacitors.
- ✓ Open the circuit in which current is to be measured - removing a fuse-link often gives a convenient point for current measurement.
- ✓ Securely connect the probes in series with the load in which the current is to be measured.
- ✓ Turn on the power to the circuit being tested.
- ✓ Note the current on the meter's display.
- ✓ Turn off the power to the circuit being tested and discharge all capacitors.
- ✓ Disconnect the test probes and switch off the instrument.
- ✓ Reconnect the circuit that was being tested.
- ✓ Often, the most convenient way to measure current in an ac circuit is to use a clamp-meter which is simply clamped around an insulated conductor.

5.1.4 Current Clamp Meters

Alternating currents in power circuits can be measured by means of a clamp meter which has a current transformer built into it. The instrument tongs are clipped round a single-insulated conductor and the circuit is not interrupted. The value of current is obtained from the magnetic flux strength around the conductor and is usually displayed on a digital display. Direct current (dc) measurement is also possible with some clamp meters that have a flux-voltage transducer known as a "Hall-effect" device.

Care must be taken when measuring the current in *un-insulated* conductors. This is because the clamp meter monitors the magnetic flux around the cable which is produced by the current. In a balanced 3-core (or 2-core for that matter) cable, the net flux is zero - hence no indication will be available. This is why the clamp meter is only connected around a single conductor.

Image Courtesy: instrumentationtools.com

Figure 5.1 – Sectional View of an AC Clamp Meter

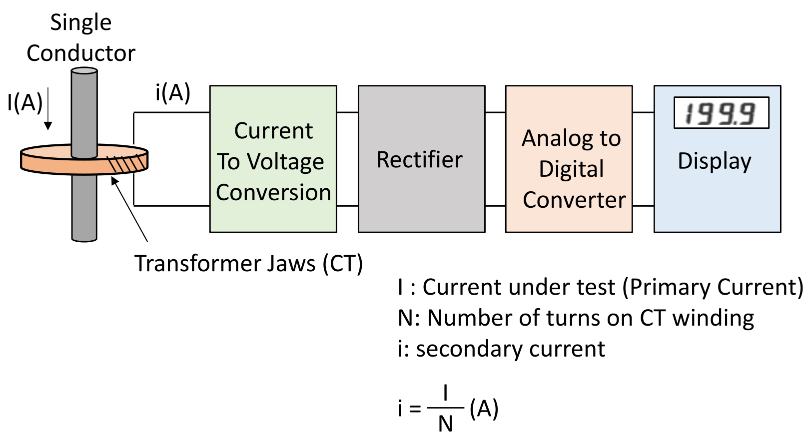


Figure 5.2 – Block Diagram for an AC Clamp Meter

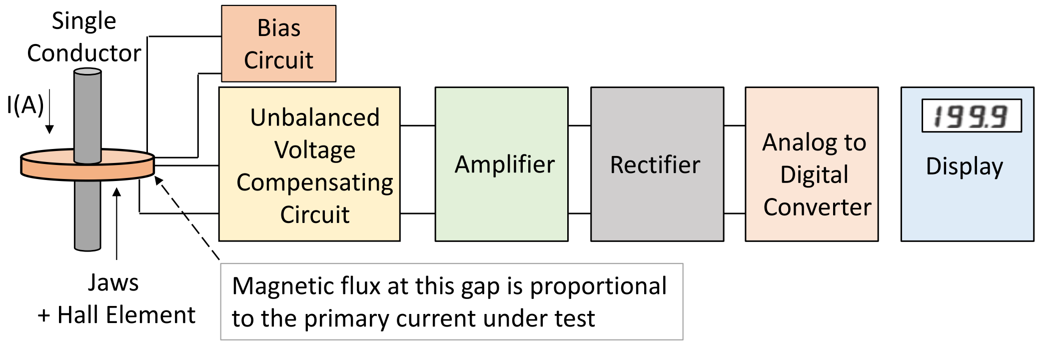


Figure 5.3 – Block Diagram for a DC Clamp Meter

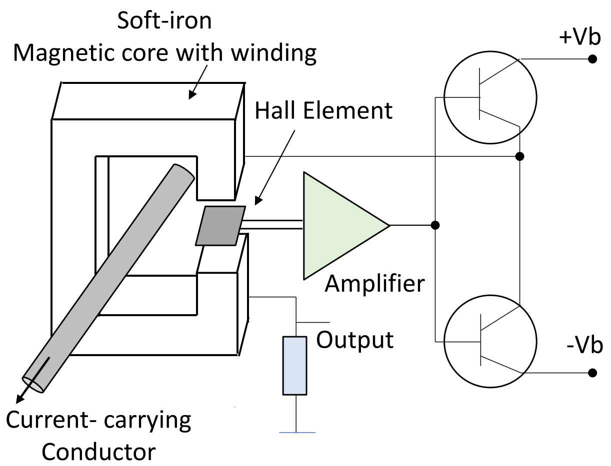


Figure 5.4 – Basic Circuit for a DC Clamp Meter

5.2 Portable Measuring Instruments

A common test instrument which is invaluable to a troubleshooter is a multimeter. It is capable of measuring voltage and resistance with some meters capable of other measurements such as current, capacitance and frequency.

A meter that is capable of measuring current, voltage and resistance is also called an AVO meter (ampere volt ohm meter). One must be able to determine what type of test instrument to use, when and where to use it, and how to safely take readings with it.

The instrument may be the traditional switched-range analog type (pointer and scale) or the more common digital type with auto-ranging and a numerical display.

Digital meters are normally designed with high impedance and therefore have high accuracy as compared to the analog types, which have low impedances. Digital meters have a clear numeric readout, which may be supported by a bar graph display.

Where distorted voltage waveforms are likely (e.g., with variable frequency motor drives), it is necessary to use a "True-RMS" meter for accuracy.

Digital meters which display the test voltage waveform shape with a storage oscilloscope facility on the LCD screen are also available.

Digital meters are useful to measure imperceptible voltages and resistances and it is also possible to measure semiconductor resistances and voltages that vary minutely.

In both analog and digital models, an internal battery serves as a voltage source when resistance values are to be measured. Before measuring the resistance of a component, it is essential that the circuit is switched-off, locked-off and any capacitor discharged; otherwise the instrument is likely to be damaged.

Images Courtesy: all-sun.com and simpsonelectric.com

Figure 5.5 – Digital and Analog Multimeters

Except for current, most of the measurements are based on voltage. For instance, while measuring resistance, a small amount of current is sent across the terminals.

The voltage drop generated is taken as an input and is divided by the current with the help of the internal circuitry to determine the resistance. The block diagram of a digital multimeter is depicted in Figure 5.6. The input is a raw analog signal and enters the internal circuitry in the form of a wave in the case of an alternating current signal.

The input signal is first conditioned where-after it proceeds to its respective measurement circuitry. Further, it is optimized for its range selection and sent to an analog-to-digital converter (ADC). Analog-to-digital converters can be of various types depending upon the capabilities of the multimeter and the manufacturer. To convert the signal, the ADC takes samples of the analog wave. To ensure signal reconstruction, the rate of sampling should be at least twice the frequency of the analog signal.

Most ADCs that are used in multimeters follow a dual slope integration method in which the digital signal is compared to a fixed reference value. The output then goes to a successive approximation register (SAR) which sends the final output to the processing unit and balances the reference signal for an optimized comparison. A clock input is needed for the SAR counter which is provided by a crystal oscillator. The processing involved in multimeters is usually limited to summing up the pulses and is more like an integrator circuit.

After the analog to digital conversion, the resultant output is then sent to the processing unit which takes the values, decodes their magnitude and sends it to the digital display unit.

Modern digital multimeters can also measure temperature and capacitance and have RS232 connectors for communication to computer terminals.

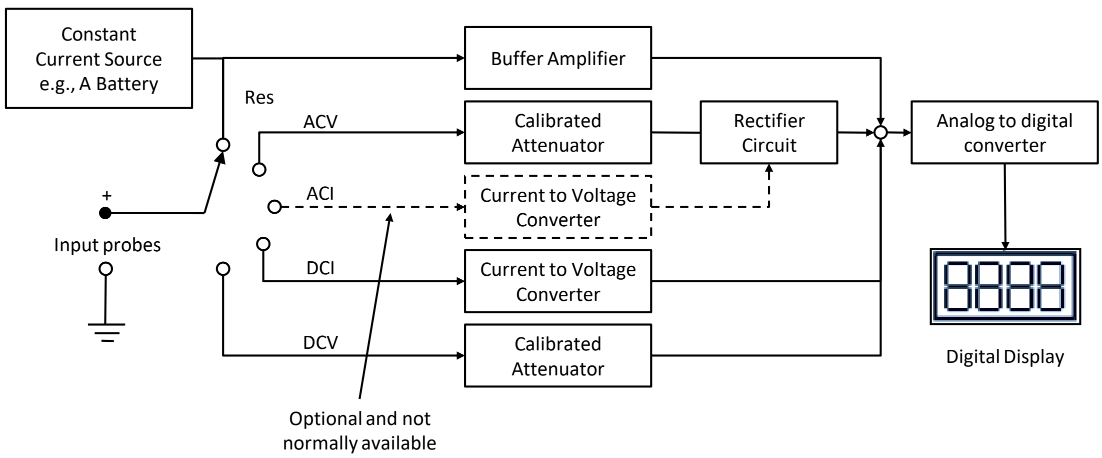


Figure 5.6 – Block Diagram of a Digital Multimeter

The operation of the multi-meter should be verified before using it in a circuit. The manufacturer's instructions should be carefully followed for this, but a general procedure is as follows:

Use the correct probes and leads and insert them into the correct sockets on the meter.

If the multi-meter is an analog type:

1. Ensure the pointer indicates zero and adjust it if it is required to do so.
2. Set the selector switch to "Ω" and connect the probe tips together. The pointer should deflect to indicate 0 Ω. If the pointer does not settle at zero, adjust the trimming control knob (an internal potentiometer). Check each resistance range in this way.
3. Instrument battery failure is checked when the instrument is set to read "Ω" with the probe tips connected as in step 2 above. If the pointer fails to reach "0 Ω" after the adjustment of the resistance range trimmer, the battery must be replaced. The instrument should be switched-off when it is not used, to preserve battery life.
4. Set the selector switch to "AC V" (at the highest range).
5. Very special care is necessary when using a multi-meter to check for live voltage. If the multi-meter has been accidentally set to the Current or Resistance range, the instrument acts as a low resistance across the live supply. The resulting short-circuit current may easily cause the meter to explode with local fire damage and very serious consequences to the operator.
6. Connect the probes to a suitable known live supply within the range of the meter, such as the electrical workshop test panel. The pointer should indicate the correct voltage.
7. Fused probe leads are highly recommended for use with a multi-meter.

If the multi-meter is of the digital type:

1. Switch on the multi-meter and check the display to see that all digits are visible and not flickering; in case the display flickers, change the cell(s). If the problem persists even after changing the battery, do not use the meter.

   Note: *if the battery is weak or discharged, accurate resistance and continuity checks will not be possible.*

2. Rotate the selector switch to each position to verify the satisfactory changeover to each mode / range. If the rotary switch is loose or faulty, DO NOT USE this meter.
3. Set selector switch to "DC V" (highest range). The display should indicate zero (000) with the probes apart.
4. Repeat this for all "DC V" selector switch positions and note the shift of the decimal point.

5. Set the selector switches to "Ω" (highest range). The display should indicate "OL" (out of or over the range) or "100" (depending upon the model). Connect the probe tips together; the display should indicate zero (000).
6. Repeat the above step for all "Ω"positions of the selector switch and note the movement of the decimal point.
7. Set the selector switch to the highest range of "AC V". Connect the probes to a suitable known live AC power supply within the range of the meter. The display should indicate the correct voltage.
8. Test the DC voltage range also and note the polarity indication on the meter.
9. The instrument's battery failure is usually indicated by the numeric display. The display may show "BT" or the decimal point may blink.
10. To preserve battery life, the instrument should be switched-off when it is not in use.
11. It must also be remembered that checking a circuit with a faulty instrument can be dangerous.

5.2.1 Procedure to Measure Continuity in a Circuit

CAUTION!

- Never measure continuity in a live circuit! The circuit must be dead and all charges discharged adequately.

a) Set the selector switch to the Continuity mode, insert the leads (red in the positive and black in the negative / common sockets) and then short the probes. The meter should display "0" (zero) and the beeper should be audible. This also establishes the fact that the leads are in good condition.

b) The continuity of a circuit is best measured when the two ends are free of connections to other branches / circuits for example, a parallel circuit.

5.2.2 Procedure to Measure Resistance

1. Prove the correct operation of the instrument as mentioned above.
2. Isolate and lock-off the equipment.
3. Prove the equipment to be dead.

4. Switch the multi-meter to the appropriate resistance range, connect the probes to the equipment to note the resistance value.

5.2.3 Procedure to Measure AC Voltage

Note: When you are not aware of the value of Voltage, set it to the maximum level e.g., 600 V~.

1. Set the rotary selector switch to the appropriate voltage setting – e.g., 600 V~ (for AC).
2. Hold the insulated probes of the leads behind the finger guard and connect the tips of the probes to a known live voltage source like a 220 V AC socket and verify that the display indicates the value as 220 V.
3. Now it is evident that the meter is capable of measuring AC voltage and is not defective.
4. Holding the insulated part of the probes, behind the finger guard, connect them across the points to be measured and note the value that is indicated.
5. No harm will be caused to the instrument by operating the selector range switches while it is connected to the live supply. But great care must be taken not to switch into either the current or resistance mode. This may cause the instrument to trip on overload and could result in possible damage to the instrument and injury to the person.
6. Once the task is completed, the meter is to be verified for proper operation by connecting it to another known, similar voltage source and verifying the value.
7. Disconnect the probes and switch off the instrument.

5.2.4 Procedure to Measure DC Voltage

Note: When you are not aware of the value of Voltage, set it to the maximum level e.g., 600 V - (for DC).

1. Generally, the multi-meter is used in the DC mode to measure battery voltages and output circuits of rectifiers. Also, it is used to measure the excitation voltages in alternators under test / maintenance.
2. Like the verification method for AC circuits above, the selector switch should be put to the appropriate DC voltage setting and first verified with a known DC voltage source and then used.

3. Holding the insulated part of the probes, behind the finger guard, connect them across the points to be measured and note the value that is indicated.
4. Once the task is completed, the meter is to be verified for proper operation by connecting it to another known DC voltage source and verifying the value.

5.2.5 Procedure to Measure Direct Current

CAUTION!

- Do not use the meter to measure starting currents.

1. A common multi-meter is designed to measure only low-current components and is particularly meant for DC electronic circuits that draw currents up to a maximum of 200 mA; there is a 10 A socket but this is only for DC and must be used very cautiously as explained below.
2. The multi-meter is NOT to be used for measuring the current drawn by AC motors and other power circuits. To measure alternating current, a clamp meter (also known as a tong tester) must be used by clamping it around one core of the cable at a time.
3. Prove the correct operation of the instrument.
4. Switch the instrument to the highest current range.
5. Turn off the power to the circuit to be tested and discharge all capacitors.
6. Open the circuit in which the current is to be measured; removing a fuse link often gives a convenient point for current measurement.
7. Securely connect the probes in series with the load in which current is to be measured.
8. If the current is anticipated to be less than and up to 200 mA, the leads can remain as in the Voltage / Continuity measurement modes.
9. If the current is anticipated to be greater than 200 mA, the Red lead should be removed and connected to the 10 A point. This will save the meter from permanent damage and the person from a serious shock which will be fatal!
10. Turn on the power to the circuit being tested; note the value of current on the meter's display
11. Turn off the power to the circuit being tested and discharge all capacitors.
12. Disconnect the test probes, switch off the instrument and reconnect the circuit that was being tested.

5.2.6 Procedure to Measure Alternating Current with a Clamp Meter

a) Switch on the meter and check the display to see that all digits are visible and not flickering; in case the displays flickers change the cell(s). If the problem persists even after changing the cell(s), do not use the meter.

Note: *if the cell(s) are weak or discharged, accurate resistance and continuity checks will not be possible.*

b) Remember that this is always used in live circuits and utmost care must be taken to prevent shocks.

c) The meter to be used must be certified and capable of measuring the maximum current in that circuit.

d) Leads are not to be connected.

e) Use the rotary switch to select the current range.

f) If you are not aware of the current range, set it to maximum – in most cases, 1000 A.

g) Hold the meter firmly and press the button on the side to open the spring-loaded clamp.

h) Place it around the conductor or core of the cable where the current is to be measured and ensure that the conductor is not under strain due to the clamp meter.

i) Care must be taken when measuring any current through an un-insulated conductor. If the clamp-meter is used around a three-core or a two-core cable, the reading will indicate zero, as the net flux in the balanced 3 or 2 cores is equal to zero.

j) Press the Hold button to record the value in case the clamp meter is used in a confined space.

Most modern clamp meters can also measure direct current with the help of Hall-effect sensors. The Fluke 376 clamp meter shown in Figure 10.40 as an example, offers improved performance that is perfect for a wide range of current measurement situations.

With true-rms voltage and current measurements, the Fluke 376 can read up to 1000 V and 1000 A in both alternating current and direct current modes. It also has min, max, average and inrush recording to capture variations automatically and filters out noise while capturing motor starting current exactly as the circuit protection sees it. Additionally, the Fluke 376 includes the new iFlex™ flexible current probe, which expands the measurement range to 2500 A ac while providing increased display flexibility, ability to measure around awkward sized conductors and improved wire access.

Images Courtesy: Fluke.com

Figure 5.7 – Analog and Digital AC and DC Clamp Meters

5.2.7 The Megger

The Mega Ohm Meter commonly known as a "megger" is used to establish the condition of insulation of electrical equipment like generators, motors and similar power systems. However, extreme caution should be exercised when using these devices as they generate between 250V and 5000V. They should be used only after the power supply to the equipment is switched off and locked off.

5.2.7.1 Constructional Features of an Analog Megger

Most ohmmeters utilize a battery of relatively low voltage, usually nine volts or less. This is adequate for measuring resistances under several mega-ohms (MΩ), but when extremely high resistances need to be measured, a 9-volt battery is insufficient for generating enough current to cause any electromechanical meter movement. Resistance is not always a stable (linear) quantity. This is especially true of non-metals.

While this is an extreme example of nonlinear conduction, other substances exhibit similar insulating / conducting properties when they are exposed to high voltages. Obviously, an ohmmeter using a low-voltage battery as a source of power cannot measure resistance at the ionization potential of a gas, or at the breakdown voltage of an insulator. If such resistance values need to be measured, nothing but a high voltage ohmmeter will suffice. A portable analog megger is shown in Figure 5.8.

Remember when $I = 0$, $R = \infty$ and vice versa.

A basic battery-operated high voltage megger works differently. It has no hand-cranking mechanism and can generate a high voltage, low-current output for insulation testing (of circuits with high dielectric strengths) and in high voltage applications.

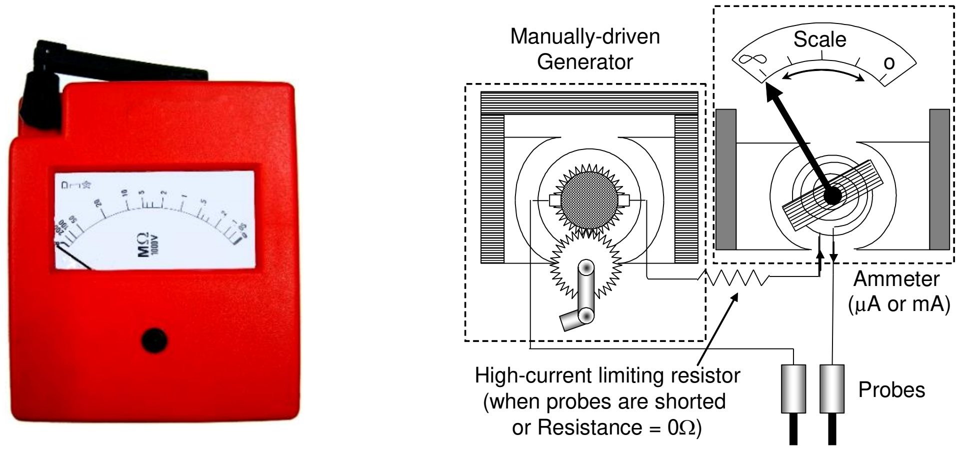


Figure 5.8 – A 500V Portable Megger and its Basic Constructional Features

A test voltage of 500 V DC is suitable for a ship's equipment that is rated at 440 V AC.

A test voltage of 1000 V DC is suitable for testing high voltage systems. However, there are devices that generate even up to 5000 V.

To test the meter, short the two probes together, switch it on and press the test button - the pointer should indicate approximately 0 MΩ. The numbered, rectangular blocks in Figure 5.9 are cross-sectional representations of wire coils. These three coils move with the needle's mechanism. There is no spring mechanism to return the needle to a set position. When the movement is not powered, the needle will randomly "float." The coils are electrically connected as depicted in Figure 5.10. With infinite resistance between the test leads (an open circuit condition), there will be n

o current through coil 1 and only through coils 2 and 3. When they are energized, these coils try to center themselves in the gap between the two magnetic poles, driving the needle fully to the right of the scale where it points to "infinity" as depicted in Figure 10.44. Any current through coil 1 (through a measured resistance connected between the test leads) tends to drive the needle to the left of scale, back to zero. The internal resistance values of the meter's movement are calibrated so that when the test leads are shorted together, the needle deflects exactly to the "0 Ω" position. As any variations in battery voltage will affect the torque generated by *both* sets of coils (coils 2 and 3, which drive the needle to the right, and coil 1, which drives the needle to the left), those variations will have no effect of the calibration of the movement.

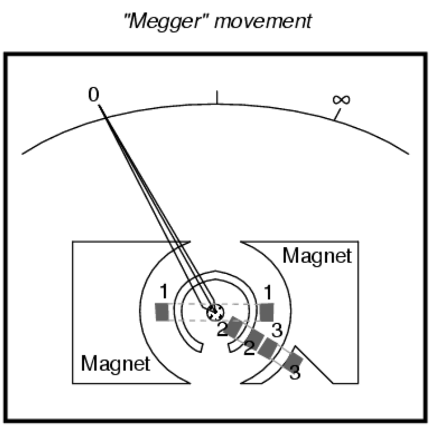


Figure 5.9 – Cross-Sectional Representations of Wire Coils

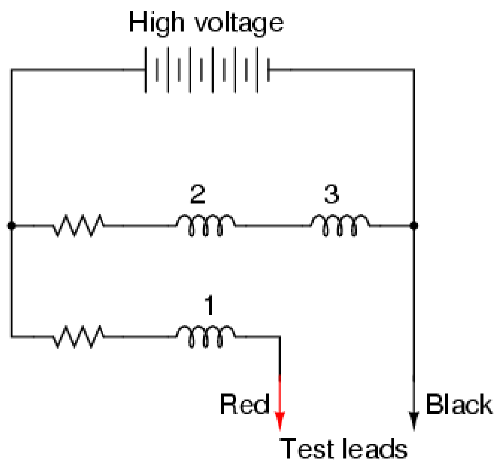


Figure 5.10
Connection of Coils in a Megger

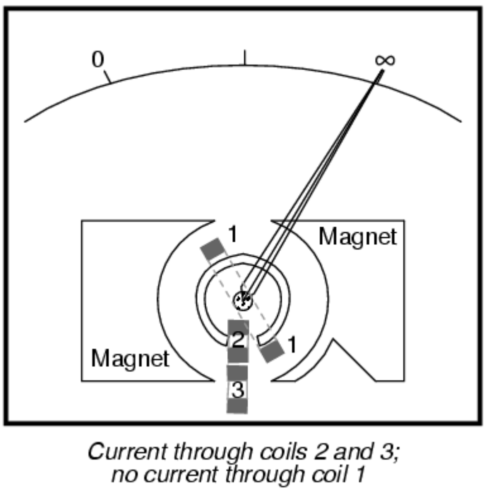


Figure 5.11
"Open Circuit" Indication

In other words, the accuracy of this ohmmeter movement is unaffected by battery voltage: a given amount of measured resistance will produce a certain deflection of the needle, no matter how much or little battery voltage is present. The only effect that a variation in voltage will have on a meter's indication is the degree to which the measured resistance changes with the applied voltage.

So, if we were to use a megger to measure the resistance of a gas-discharge lamp, it would read very high resistance (the needle deflects to the far right of the scale) for low voltages and low resistance (the needle deflects to the left of the scale) for high voltages. This is precisely what we expect from a good high-voltage ohmmeter: to provide accurate indication of resistance under different circumstances.

5.2.7.2 Safety Features

For maximum safety, most meggers are equipped with hand-crank generators for producing the high DC voltage (500 V to 1000 V). Hence the crocodile clips must never be touched with bare hands when the device is in use. If the operator of the meter receives a shock from the high voltage, the condition will be self-correcting, as he or she will naturally stop cranking the generator! Sometimes a “slip clutch” is used to stabilize the generator’s speed under different cranking conditions, so as to provide a fairly stable voltage whether it is cranked fast or slow. Multiple voltage output levels from the generator are available by the setting of a selector switch.

Some meggers are battery-powered to provide greater precision in the output voltage. For safety reasons these meggers are activated by a momentary-contact pushbutton switch, so the switch cannot be left in the “on” position and pose a significant shock hazard to the meter operator.

Never use this device on electronic components and associated circuits e.g., an AVR or a PCB in a boiler.

Never use a megger or portable insulation tester in a live circuit. The circuit / equipment e.g., a motor must be dead and isolated from all sources of power.

5.2.7.3 Procedure to Use a Portable Megger / Insulation Tester

a) These devices can generate 500 V or 1000 V DC and hence the crocodile clips must never be touched with bare hands when the device is in use.

b) The Insulation tester must be grounded and all static charged dissipated before using the tester.

c) To ensure that this device is functioning, press the test button or rotate the handle to see that it indicates infinity without the probes being shorted. Now short the crocodile clips and repeat the process; the meter should read zero.

d) Never use this device on electronic components and circuits e.g., an AVR or PCB / PLC in a boiler.

e) Never use a megger or portable insulation tester in a live circuit. The circuit / equipment e.g., a motor must be dead and isolated from all sources of power.

ELTK1200 Formula Sheet

Induced voltage

$$V_{ind} = NB\ell v \sin\theta$$

$$v = V_M \sin\theta$$

$$v = V_M \sin(\omega t)$$

$$v = V_M \sin(2\pi f t)$$

Frequency

$$f = \frac{1}{T}$$

Angular velocity

$$\omega = 2\pi f$$

Peak, Peak to Peak, RMS

$$V_P = V_M \qquad V_{PP} = 2V_M$$

$$V_{RMS} = \frac{V_M}{\sqrt{2}} = 0.707\,V_M$$

$$I_P = I_M \qquad I_{PP} = 2I_M$$

$$I_{RMS} = \frac{I_M}{\sqrt{2}} = 0.707\,I_M$$

Real Inductor

$$Z_{coil} = \sqrt{R_{Eff}^2 + X_L^2}$$

$$R_{Eff} = R_{dc} + R_{ac}$$

Q-Factor

$$Q\text{-}factor = \frac{X_L}{R_{Eff}} = \frac{2\pi f L}{R_{Eff}}$$

Power Factor

$$p.f. = \frac{P}{S} = \cos\theta \quad \textit{leading/lagging}$$

Capacitance

$$C = \frac{q}{V}$$

$$C = \frac{8.85 * 10^{-12} A\,k}{d}$$

Resistors in series

$$R_T = R_1 + R_2 + R_3 + \dots$$

Resistors in parallel

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

Capacitors in series

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$

Capacitors in parallel

$$C_T = C_1 + C_2 + C_3 + \dots$$

Inductors in series

$$L_T = L_1 + L_2 + L_3 + \dots$$

Inductors in parallel

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots$$

Pure resistor

Instantaneous equations

$$v_S = V_M \sin(\omega t)$$

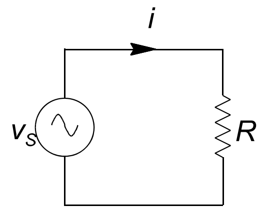
$$i = I_M \sin(\omega t)$$

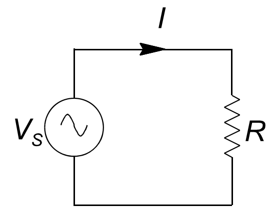
$$p = P_M \sin^2(\omega t)$$

$$I_M = \frac{V_M}{R}$$

$$P_M = V_M I_M = I_M^2 R = \frac{V_M^2}{R}$$

$$P_{AVG} = \frac{P_M}{2} = \frac{V_M I_M}{2} = \frac{I_M^2 R}{2} = \frac{V_M^2}{(2R)}$$



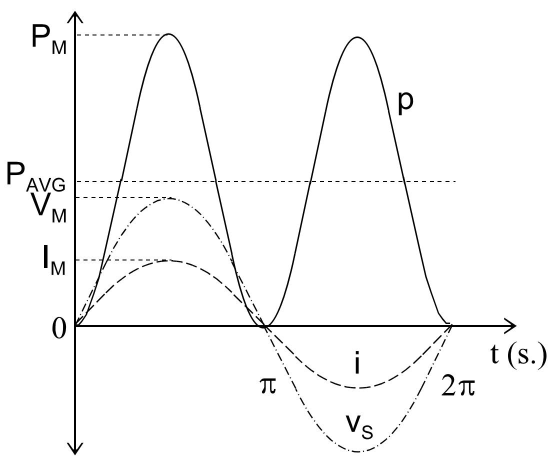


RMS

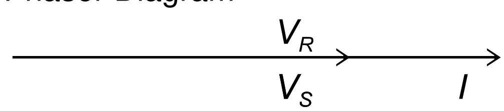
$$I = \frac{V_S}{R}$$

$$P = V_S I = I^2 R = \frac{V_S^2}{R} = P_{AVG}$$

Instantaneous waveforms



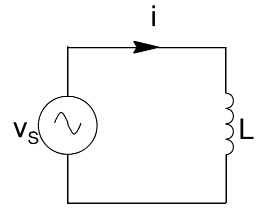
Phasor Diagram

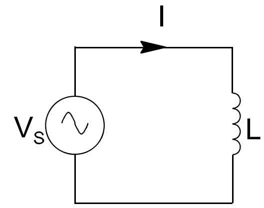


Phase Relationship:
I and V_S are "in phase".

Pure inductor

$X_L = 2\pi f L$





Instantaneous equations

I as reference.

$$v_S = V_M \sin\left(\omega t + \frac{\pi}{2}\right) = V_M \sin(\omega t + 90°)$$

$$i = I_M \sin(\omega t)$$

V_S as reference (See Note).

$$v_S = V_M \sin(\omega t)$$

$$i = I_M \sin\left(\omega t - \frac{\pi}{2}\right) = I_M \sin(\omega t - 90°)$$

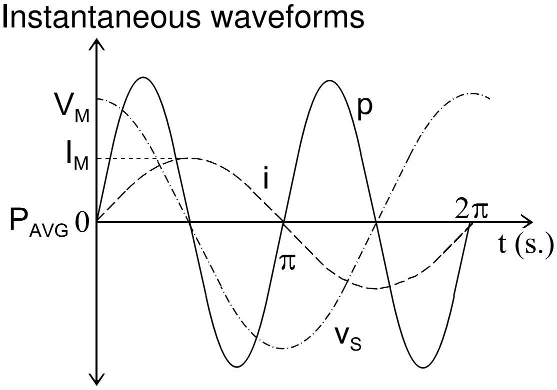
RMS

$$I = \frac{V_S}{X_L}$$

$$Q_L = V_S I = I^2 X_L = \frac{V_S^2}{X_L}$$

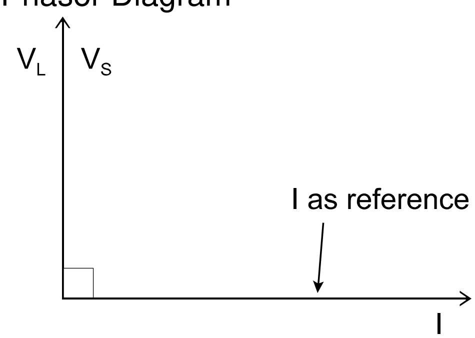
$$P = 0$$

Instantaneous waveforms



I as reference (starts at 0).

Phasor Diagram



Phase Relationship:
I lags V_S by 90°.

Note: The instantaneous equations depend upon which waveform is taken as a reference. Phasor diagrams use current I as a reference, but sometimes problems give V_S as reference ($v_S = V_M \sin(\omega t)$) and you must calculate I.

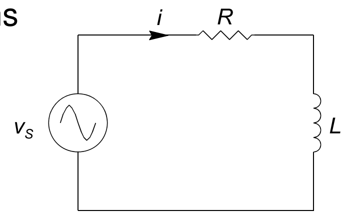
For the rest of this formula sheet, current I will be the reference.

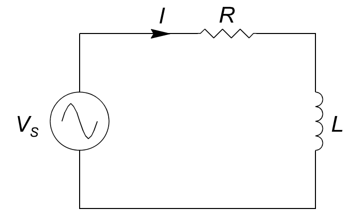
Series RL circuit

Instantaneous equations

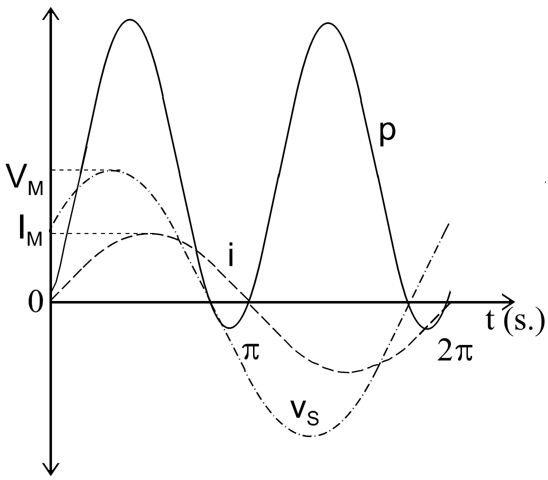
$$v_S = V_M \sin(\omega t + \theta)$$

$$i = I_M \sin(\omega t)$$





Instantaneous waveforms



RMS

$$I = \frac{V_S}{Z}$$

Impedance Triangle

$$Z = \sqrt{R^2 + X_L^2} = \frac{V_S}{I}$$

$$R = \frac{V_R}{I} = Z\cos\theta$$

$$X_L = \frac{V_L}{I} = Z\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{X_L}{R}\right) \quad \textit{lagging}$$

Phasor Diagram

$$V_S = \sqrt{V_R^2 + V_L^2} = IZ$$

$$V_R = IR = V_S\cos\theta$$

$$V_L = IX_L = V_S\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{V_L}{V_R}\right) \quad \textit{lagging}$$

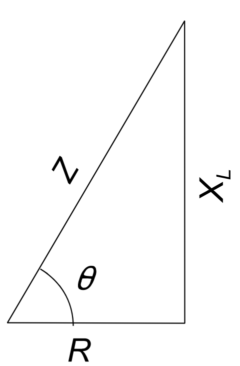
Power Triangle

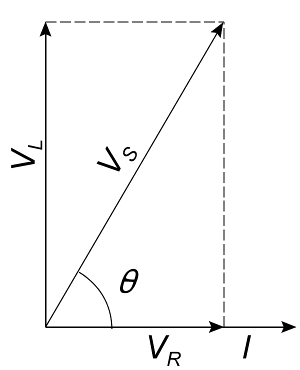
$$S = \sqrt{P^2 + Q_L^2} = V_S I = I^2 Z = \frac{V_S^2}{Z}$$

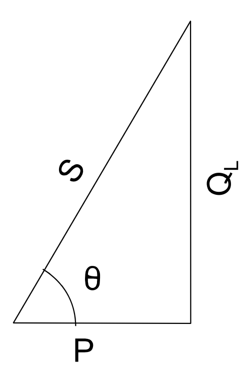
$$P = V_R I = I^2 R = \frac{V_R^2}{R} = S\cos\theta$$

$$Q_L = V_L I = I^2 X_L = \frac{V_L^2}{X_L} = S\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{Q_L}{P}\right) \quad \textit{lagging}$$



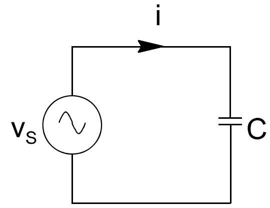


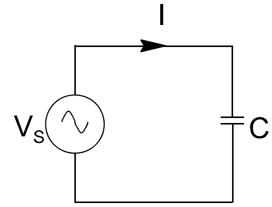


Phase Relationship: I lags V_S by θ (angle between 0° and 90°).

Pure capacitor

$$X_C = \frac{1}{(2\pi f C)}$$





Instantaneous equations

$$v_S = V_M \sin\left(\omega t - \frac{\pi}{2}\right) = V_M \sin(\omega t - 90°)$$

$$i = I_M \sin(\omega t)$$

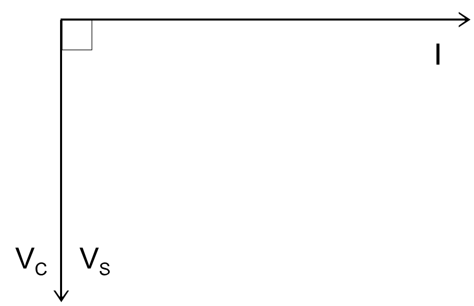
RMS

$$I = \frac{V_S}{X_C}$$

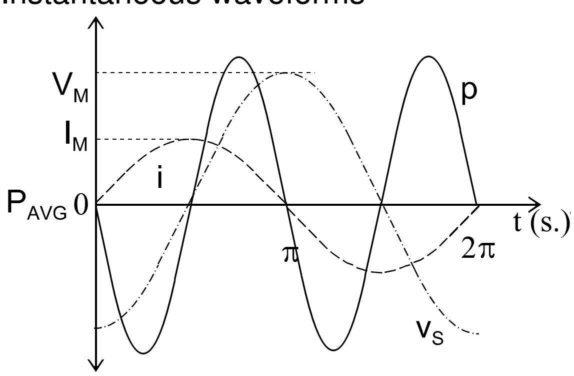
$$Q_C = V_S I = I^2 X_C = \frac{{V_S}^2}{X_C}$$

$$P = 0$$

Phasor Diagram



Instantaneous waveforms



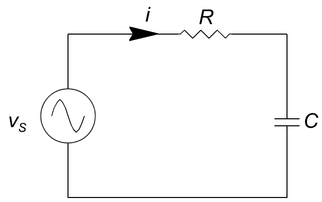
Phase Relationship:
I leads V_S by 90°.

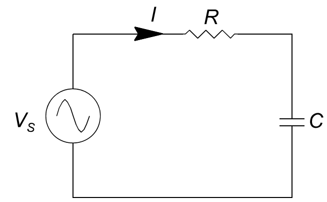
Series RC circuit

Instantaneous equations

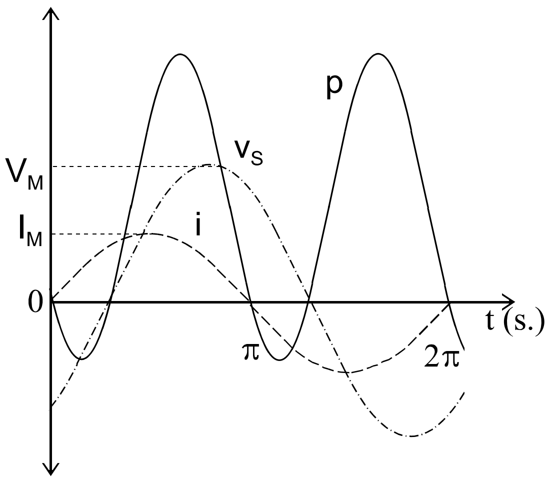
$$v_S = V_M \sin(\omega t - \theta)$$

$$i = I_M \sin(\omega t)$$





Instantaneous waveforms



RMS

$$I = \frac{V_S}{Z}$$

Impedance Triangle

$$Z = \sqrt{R^2 + X_C^2} = \frac{V_S}{I}$$

$$R = \frac{V_R}{I} = Z\cos\theta$$

$$X_C = \frac{V_C}{I} = Z\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{X_C}{R}\right) \quad \textit{leading}$$

Phasor Diagram

$$V_S = \sqrt{V_R^2 + V_C^2} = IZ$$

$$V_R = IR = V_S\cos\theta$$

$$V_C = IX_C = V_S\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{V_C}{V_R}\right) \quad \textit{leading}$$

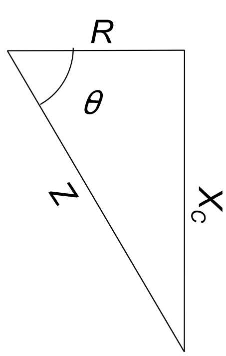
Power Triangle

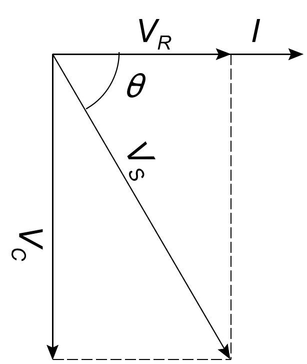
$$S = \sqrt{P^2 + Q_C^2} = V_S I = I^2 Z = \frac{V_S^2}{Z}$$

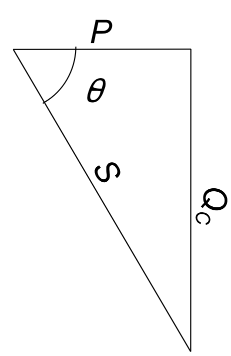
$$P = V_R I = I^2 R = \frac{V_R^2}{R} = S\cos\theta$$

$$Q_C = V_C I = I^2 X_C = \frac{V_C^2}{X_C} = S\sin\theta$$

$$\theta = \tan^{-1}\left(\frac{Q_C}{P}\right) \quad \textit{leading}$$



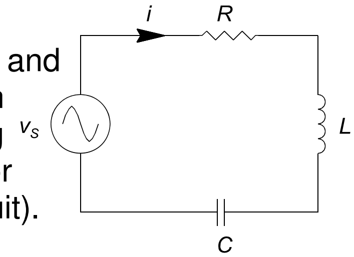


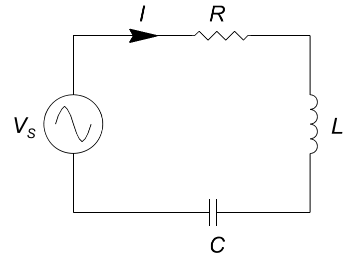


Phase Relationship: I leads V_S by θ (angle between 0° and 90°).

Series RLC circuit

Instantaneous equations and waveforms depend on whether the angle is lagging (See Series RL circuit) or leading (See Series RC circuit).





NOTE: If $X_L > X_C$ ($V_L > V_C$, $Q_L > Q_C$), circuit is inductive, ∴ lagging phase angle. If $X_L < X_C$ ($V_L < V_C$, $Q_L < Q_C$), circuit is capacitive, ∴ leading phase angle. If $X_L = X_C$ ($V_L = V_C$, $Q_L = Q_C$), circuit is resistive, ∴ in phase, resonant frequency.

RMS

$$I = \frac{V_S}{Z}$$

Impedance Triangle

$$X_{NET} = X_L \sim X_C$$

$$Z = \sqrt{R^2 + X_{NET}^2} = \frac{V_S}{I}$$

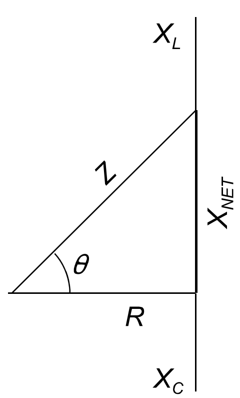
$$R = \frac{V_R}{I} = Z\cos\theta$$

$$X_{NET} = \frac{V_{NET}}{I} = Z\sin\theta$$

$$X_L = \frac{V_L}{I}$$

$$X_C = \frac{V_C}{I}$$

$$\theta = \tan^{-1}\left(\frac{X_{NET}}{R}\right) \quad NOTE$$



Phasor Diagram

$$V_{NET} = V_L \sim V_C$$

$$V_S = \sqrt{V_R^2 + V_{NET}^2} = IZ$$

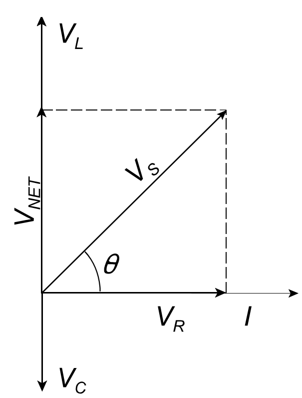
$$V_R = IR = V_S\cos\theta$$

$$V_{NET} = IX_{NET} = V_S\sin\theta$$

$$V_L = IX_L$$

$$V_C = IX_C$$

$$\theta = \tan^{-1}\left(\frac{V_{NET}}{V_R}\right) \quad NOTE$$



Power Triangle

$$Q_{NET} = Q_L \sim Q_C$$

$$S = \sqrt{P^2 + Q_{NET}^2} = V_S I = I^2 Z = \frac{V_S^2}{Z}$$

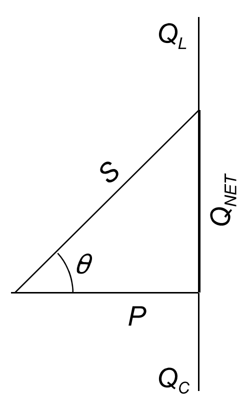
$$P = V_R I = I^2 R = \frac{V_R^2}{R} = S\cos\theta$$

$$Q_{NET} = V_{NET} I = I^2 X_{NET} = \frac{V_{NET}^2}{X_{NET}} = S\sin\theta$$

$$Q_L = V_L I = I^2 X_L = \frac{V_L^2}{X_L}$$

$$Q_C = V_C I = I^2 X_C = \frac{V_C^2}{X_C}$$

$$\theta = \tan^{-1}\left(\frac{Q_{NET}}{P}\right) \quad NOTE$$



Phase Relationship: I leads/lags V_S by θ (between 0° and 90°). Lagging phase angle shown. See NOTE.

Resonant frequency

$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

$$Q_{factor} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{X_L}{R_{Eff}}$$

$$BW = \frac{f_R}{Q_{factor}}$$

$$f_1 = f_R - \frac{BW}{2}$$

$$f_2 = f_R + \frac{BW}{2}$$

$$I_{cut-off} = 0.707\ I_{MAX_{RMS}}$$

General Transformer equation

$$V_1 = 4.44\ f\ N_1\ \Phi_M$$
$$V_2 = 4.44\ f\ N_2\ \Phi_M$$

Transformation ratio

$$\alpha = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

Transformer capacity

$$I_{2\ (Full-load)} = \frac{rated\ kV \cdot A}{V_2}$$

$$I_{1\ (Full-load)} = \frac{rated\ kV \cdot A}{V_1}$$

$$P_{2\ (Full-load)} = rated\ kV \cdot A\ *\ p.f.$$

Three phase

Wye (Y)

$$I_{Line} = I_{Phase}$$

$$V_{Line} = \sqrt{3}\ V_{Phase}$$

Delta (Δ)

$$I_{Line} = \sqrt{3}\ I_{Phase}$$

$$V_{Line} = V_{Phase}$$

Power

$$P_T = \sqrt{3}\ V_{Line}\ I_{Line}\ \cos\theta$$

$$P_T = 3\ V_{Phase}\ I_{Phase}\ \cos\theta$$

Relationship between I and V_S for all Series Circuits.

Inductive	L	I lags V_S by 90°.
	RL	I lags V_S by θ. [2]
Resistive	R	I and V_S are in phase.
Capacitive	RC	I leads V_S by θ. [2]
	C	I leads V_S by 90°.
[1]	RLC	I leads/lags V_S by θ. [1]

[1] Depends on values of L, C and f.
[2] between 0° and 90°.

ELI the **ICE**man drinks **RIE**.
ELI drinks **RIE** and **ICE**.

ELI = I lags V_S by 90° for L circuits.
RIE = I and V_S are in phase for R circuits.
ICE = I leads V_S by 90° for C circuits.

Transformer losses and efficiency

$$Copper\ loss = Cu\ loss = I_1^2\ R_1 + I_2^2\ R_2$$

$$Efficiency = \eta = \frac{output}{input} * 100\% = \frac{output}{output + losses} * 100\%$$

$$Efficiency = \frac{P_{out}}{P_{in}} * 100\% = \frac{P_2}{P_1} * 100\% = \frac{S_{out}}{S_{in}} * 100\% = \frac{S_2}{S_1} * 100\%$$

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ABOUT THE BOOK

This book is compiled to help both pre-sea cadets and officers of post sea courses get a clear understanding of Basic Electricity, which is so important in the shipping industry these days. Efforts have been made to align the topics to the requirements of the IMO Model Courses for Marine Engineers at the Management and Operation Level and also for Electro Technical Officers.

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