Amateur Wireless Station Operators License Exam

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CHAPTER 2

Chapter 2 : ELEMENTARY THEORY OF ALTERNATING CURRENTS:

WHAT IS ALTERNATING CURRENT (A.C.)?

Alternating current is the current which constantly changes in amplitude, and which reverses direction at regular intervals. We know that direct current flows only in one direction, and that the amplitude of current is determined by the number of electrons flowing past a point in a circuit in one second. If, for example, a coulomb of electrons moves past a point in a wire in one second and all of the electrons are moving in the same direction,the amplitude of direct current in the wire is one ampere. Similarly, if half a coulomb of electrons moves in one direction past a point in the wire in half a second, then reverses direction and moves past the same point in the opposite direction during the next half-second, a total of one coulomb of electrons passes the point in one second.The amplitude of the alternating current is one ampere
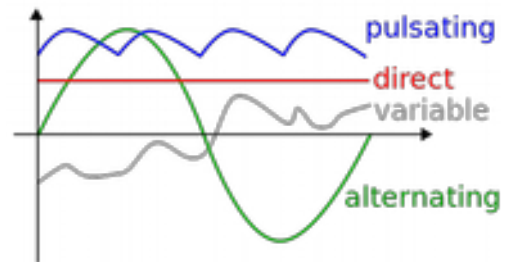
DISADVANTAGES OF D.C. COMPARED TO A.C.

Disadvantage of the direct-current system becomes evident when the direct current (I) from the generating station must be transmitted a long distance over wires to the consumer. When this happens, a large amount of power is lost due to the resistance (R) of the wire. The power loss is equal to I^2R. However, this loss can be greatly reduced if the power is transmitted over the lines at a very high voltage level and a low current level. This is not a practical solution to the power loss in the d.c. system since the load would then have to be operated at a dangerously high voltage. Because of the disadvantages related to transmitting and using direct current, practically all modern commercial electricpower companies generate and distribute alternating current. (a.c.).Unlike direct voltages, alternating voltages can be stepped up or down in amplitude by a device called a transformer. Use of the transformer permits efficient transmission of electricalpower over long-distance lines. At the electrical power station,the transformer output power is at high voltage and low current levels. At the consumer end of the transmission lines, the voltage is stepped down by a transformer to the value required by the load. Due to its inherent advantages and versatility, alternating current has replaced direct current in all but a few commercial power distribution systems.

PROPERTIES OF ALTERNATING CURRENT

A D.C. power source, such as a battery, outputs a constant voltage over time, once the chemicals in the battery have completed their reaction, the battery will be exhausted and cannot develop any output voltage. But until that happens, the output voltage to the right will remain essentially constant. The same is true for any other source of D.C. electricity: the output voltage remains constant over time.By contrast, an A.C. source of electrical power changes constantly in amplitude and regularly here. Because the changes are so regular, alternating voltage and current have a number of properties associated with any such waveform. These basic properties include the following list:

Frequency: One of the most important properties of any regular waveform identifies the number of complete cycles it goes through in a fixed period of time. For standard measurements, the period of time is one second, so the frequency of the wave is commonly measured in cycles per second (cycles/ sec) and, in normal usage, is expressed in units of Hertz (Hz). It is represented in mathematical equations by the letter '*f*'.

Period: Sometimes we need to know the amount of time required to complete one cycle of the waveform, rather than the number of cycles per second of time. This is logically the reciprocal of frequency. Thus, period is the time duration of one cycle of the waveform, and is measured in seconds/ cycle.

Wavelength: Because an A.C. wave moves physically as well as changing in time, sometimes we need to know how far it moves in one cycle of the wave, rather than how long that cycle takes to complete. This of course depends on how fast the wave is moving as well. The Greek letter (lambda) is used to represent wavelength in mathematical expressions. And, $\lambda = c/f$. As shown in the figure to the above, wavelength can be measured from any part of one cycle to the equivalent point in the next cycle. Wavelength is very similar to period as discussed above, except that wavelength is measured in distance per cycle while period is measured in time per cycle.

Amplitude: Mathematically, the amplitude of a sine wave is the value of that sine wave at its peak. This is the maximum value, positive or negative, that it can attain. However, when we speak of an A.C. power system, it is more useful to refer to the effective voltage or current.

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ALTERNATING CURRENT VALUES

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THE SINE WAVE

A sine wave or sinusoid is a waveform whose graph is identical to the generalized sine function
$$y = A \sin[\omega(x - a)] + C$$
where A is the amplitude, ω is the angular frequency ($2\pi/P$ where P is the wavelength), a is the phase shift, and C is the vertical offset.This wave pattern occurs often in nature, including in ocean waves, sound waves, and light waves.

Any wave shape, such as square waves or even the irregular sounds waves made by human speech.The human ear can recognize single sine waves because they sound "clean" or "clear" to us; some sounds that approximate a pure sine wave are whistling, a crystal glass set to vibrate by running a wet finger around its rim, and the sound made by a tuning fork.To the human ear, a sound that is made up of more than one sine wave will either sound "noisy" or will have detectable harmonics.

λ = *wavelength*
y = *amplitude*
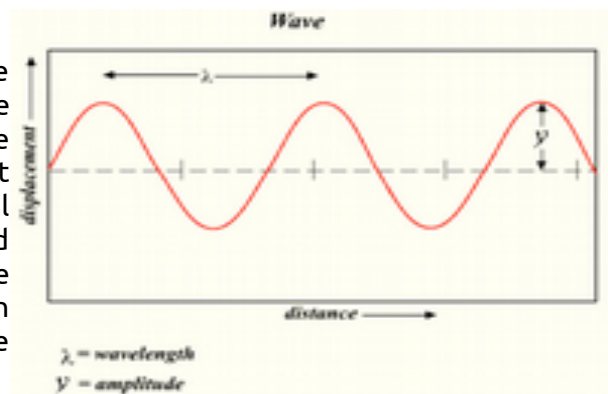
In discussing alternating current and voltage, we will often find it necessary to express the current and voltage in terms of MAXIMUM or PEAK values, PEAK-to-PEAK values, EFFECTIVE values, AVERAGE values, or INSTANTANEOUS values. Each of these values has a different meaning and is used to describe a different amount of current or voltage.

PEAK AND PEAK-TO-PEAK VALUES

Refer to figure . Notice it shows the positive alternation of a sine wave (a half-cycle of ac) and a dc waveform that occur simultaneously. Note that the dc starts and stops at the same moment as does the positive alternation, and that both waveforms rise to the same maximum value. However, the dc values are greater than the corresponding ac values at all points except the point at which the positive alternation passes through its maximum value. At this point the dc and ac values are equal. This point on the sine wave is referred to as the maximum or peak value.
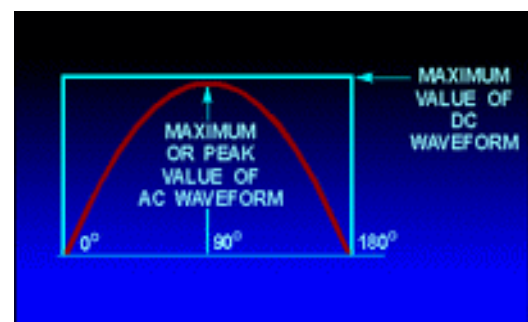
During each complete cycle of ac there are always two maximum or peak values, one for the positive half-cycle and the other for the negative half-cycle. The difference between the peak positive value and the peak negative value is called the peak-to-peak value of the sine wave. This value is twice the maximum or peak value of the sine wave and is sometimes used for measurement of ac voltages.

Note the difference between peak and peak-to-peak values in figure . Usually alternating voltage and current are expressed in EFFECTIVE VALUES (a term you will study later) rather than in peak-to-peak values.
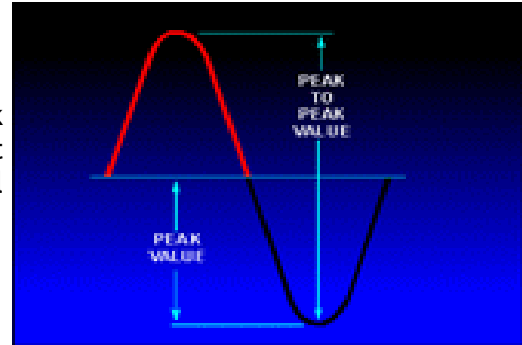
INSTANTANEOUS VALUE

The INSTANTANEOUS value of an alternating voltage or current is the value of voltage or current at one particular instant. The value may be zero if the particular instant is the time in the cycle at which the polarity of the voltage is changing. It may also be the same as the peak value, if the selected instant is the time in the cycle at which the voltage or current stops increasing and starts decreasing. There are actually an infinite number of instantaneous values between zero and the peak value.

AVERAGE VALUE

The AVERAGE value of an alternating current or voltage is the average of ALL the INSTANTANEOUS values during ONE alternation. Since the voltage increases from zero to peak value and decreases back to zero during one alternation, the average value must be some value between those two limits. You could determine the average value by adding together a series of instantaneous values of the alternation (between 0° and 180°), and then dividing the sum by the number of instantaneous values used. The computation would show that one alternation of a sine wave has an average value equal to 0.636 times the peak value. The formula for average voltage is

E_{avg} = 0.636 X E_{max}

where E_{avg} is the average voltage of one alternation, and E_{max} is the maximum or peak voltage. Similarly, the formula for average current is

I_{avg} = 0.636 X I_{max}

where I_{avg} is the average current in one alternation, and I_{max} is the maximum or peak current.

Do not confuse the above definition of an average value with that of the average value of a complete cycle. Because the voltage is positive during one alternation and negative during the other alternation, the average value of the voltage values occurring during the complete cycle is zero.

EFFECTIVE VALUE OF A SINE WAVE

E_{max}, E_{avg}, I_{max}, and I_{avg} are values used in ac measurements. Another value used is the EFFECTIVE value of ac This is the value of alternating voltage or current that will have the same effect on a resistance as a comparable value of direct voltage or current will have on the same resistance.

In an earlier paragraph you were told that when current flows in a resistance, heat is produced. When direct current flows in a resistance, the amount of electrical power converted into heat

equals I^2R watts. However, since an alternating current having a maximum value of 1 ampere does not maintain a constant value, the alternating current will not produce as much heat in the resistance as will a direct current of 1 ampere.

Figure compares the heating effect of 1 ampere of DC to the heating effect of 1 ampere of AC.
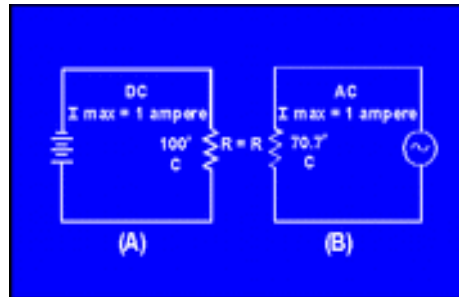

Figure 1 - Heating effect of AC and DC.

Examine views A and B of figure 1 and notice that the heat (70.7° C) produced by 1 ampere of alternating current (that is, an ac with a maximum value of 1 ampere) is only 70.7 percent of the heat (100° C) produced by 1 ampere of direct current. Mathematically,

$$\frac{\text{The heating effect of 1 maximum a.c. ampere}}{\text{The heating effect of 1 maximum d.c. ampere}} = \frac{70.7°\,C}{100°\,C} = 0.707$$

Therefore, for effective value of AC (I_{eff}) = 0.707 X I_{max}.

The rate at which heat is produced in a resistance forms a convenient basis for establishing an effective value of alternating current, and is known as the "heating effect" method. An alternating current is said to have an effective value of one ampere when it produces heat in a given resistance at the same rate as does one ampere of direct current.

You can compute the effective value of a sine wave of current to a fair degree of accuracy by taking equally-spaced instantaneous values of current along the curve and extracting the square root of the average of the sum of the squared values.

For this reason, the effective value is often called the "root-mean-square" (rms) value. Thus,

$$I_{eff} = \sqrt{\text{Average of the sum of the squares of } I_{inst.}}$$

Stated another way, the effective or rms value (I_{eff}) of a sine wave of current is 0.707 times the maximum value of current (I_{max}). Thus, I_{eff} = 0.707 X I_{max}. When I_{eff} is known, you can find I_{max} by using the formula I_{max} = 1.414 X I_{eff}.

You might wonder where the constant 1.414 comes from. To find out, examine figure (1) again and read the following explanation. Assume that the dc in figure (1-A) is maintained at 1 ampere and the resistor temperature at 100°C. Also assume that the AC in figure (1-B) is increased until the temperature of the resistor is 100° C. At this point it is found that a maximum AC value of 1.414 amperes is required in order to have the same heating effect as direct current. Therefore, in the ac circuit the maximum current required is 1.414 times the effective current. It is important for you to remember the above relationship and that the effective value (I_{eff}) of any sine wave of current is always 0.707 times the maximum value (I_{max}).

Since alternating current is caused by an alternating voltage, the ratio of the effective value of voltage to the maximum value of voltage is the same as the ratio of the effective value of current to the maximum value of current. Stated another way, the effective or rms value (E $_{eff}$) of a sine-wave of voltage is 0.707 times the maximum value of voltage (E$_{max}$),

$$E_{eff} = \sqrt{\text{Average of the sum of the squares of } E_{inst}}$$

or,

$$E_{eff} = 0.707 \times E_{max}$$

and

$$E_{max} = 1.414 \times E_{eff}$$

When an alternating current or voltage value is specified in a book or on a diagram, the value is an effective value unless there is a definite statement to the contrary. Remember that all meters, unless marked to the contrary, are calibrated to indicate effective values of current and voltage.

Problem: A circuit is known to have an alternating voltage of 120 volts and a peak or maximum current of 30 amperes. What are the peak voltage and effective current values?

Given:
$$E_s = 120\,V$$
$$E_{max} = 30\,A$$

Solution:
$$E_{max} = 1.414 \times E_{eff}$$
$$E_{max} = 1.414 \times 120\,\text{volts}$$
$$E_{max} = 169.68\,\text{volts}$$
$$I_{eff} = 0.707 \times I_{max}$$
$$I_{eff} = 0.707 \times 30\,\text{amperes}$$
$$I_{eff} = 21.21\,\text{amperes}$$

Figure shows the relationship between the various values used to indicate sine-wave amplitude. Review the values in the figure to ensure you understand what each value indicates.
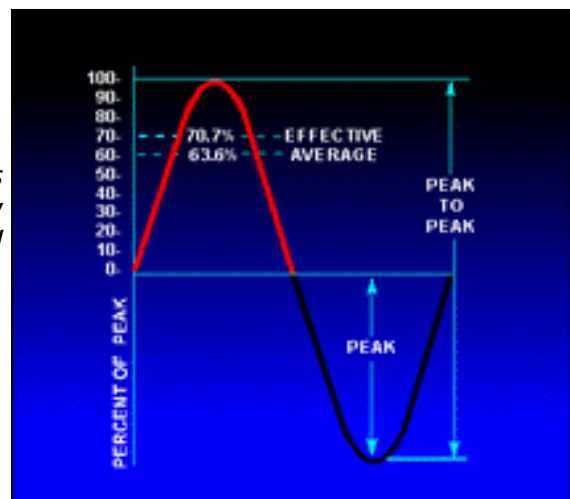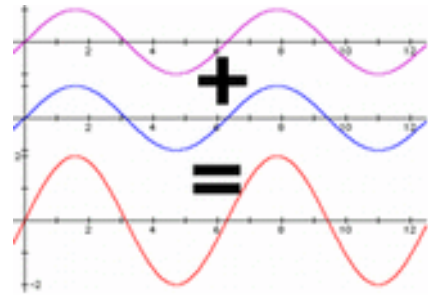

Phase

Phase, is the fraction of a period (i.e., the time required to complete a full cycle) that a point completes after last passing through the reference, or zero, position. For example, the reference position for the hands of a clock is at the numeral 12, and the minute hand has a period of one hour. At a quarter past the hour the minute hand has a phase of one-quarter period, having

passed through a phase angle of 90°, or π/2 radians. In this example the motion of the minute hand is a uniform circular motion, but the concept of phase also applies to simple harmonic motion such as that experienced by waves and vibrating bodies.

Phase difference

Phase difference is the difference, expressed in electrical degrees or time, between two waves having the same frequency and referenced to the same point in time.Two oscillators that have the same frequency and different phases have a phase difference, and the oscillators are said to be out of phase with each other. The amount by which such oscillators are **out of phase** with each other can be expressed in degrees from 0° to 360°, If the phase difference is 180 degrees (π radians), then the two oscillators are said to be in **antiphase**. If two interacting waves meet at a point where they are in antiphase, then destructive interference will occur. It is common for waves of electromagnetic (light, RF), acoustic (sound) or other energy to become superposed in their transmission medium. When that happens, the phase difference determines whether they reinforce or weaken each other. Complete cancellation is possible for waves with equal amplitudes.


Time is sometimes used (instead of angle) to express position within the cycle of an oscillation. A phase difference is analogous to two athletes running around a race track at the same speed and direction but starting at different positions on the track. They pass a point at different instants in time. But the time difference (phase difference) between them is a constant - same for every pass since they are at the same speed and in the same direction. If they were at different speeds (different frequencies), the phase difference is undefined and would only reflect different starting positions. Technically, phase difference between two entities at various frequencies is undefined and does not exist.
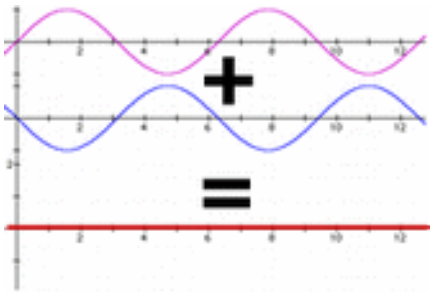
When comparing the phases of two or more periodic motions, such as waves, the motions are said to be in phase when corresponding points reach maximum or minimum displacements simultaneously. If the crests of two waves pass the same point or line at the same time, then they are **in phase** for that position; however, if the crest of one and the trough of the other pass at the same time, the phase angles differ by 180°, or π radians, and the waves are said to be **out of phase** (by 180° in this case).

Phase shift

Phase shift is any change that occurs in the phase of one quantity, or in the phase difference between two or more quantities.
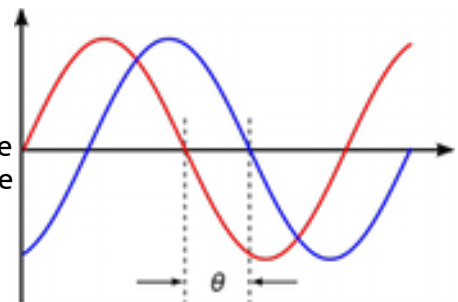
Uses

The measurement of phase difference is of central importance in alternating-current technology. In the diagram, two curves represent the voltage (E) and the current (I) in an alternating-current (AC) circuit with pure inductance. The difference in phase angle between the voltage and the current is 90°, and the current is said to lag one-quarter cycle in phase. This lag may be seen from the diagram. In AC power transmission the terms multiphase and polyphase are applied to currents that are out of phase with one another. In a two-phase system there are two currents with a phase-angle difference of 90°; in a three-phase system the currents differ in phase angle by 120°.
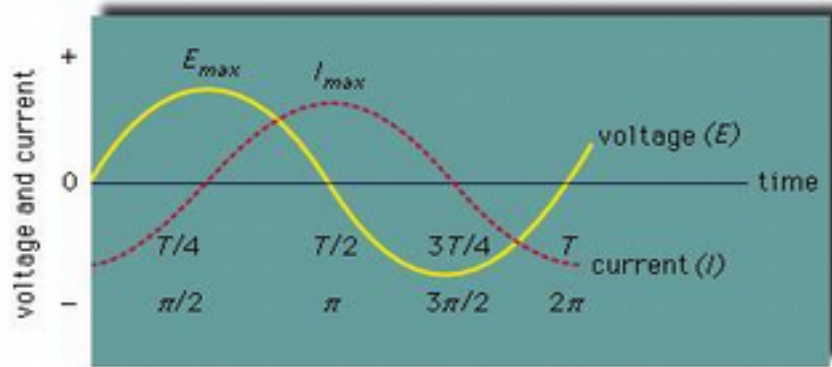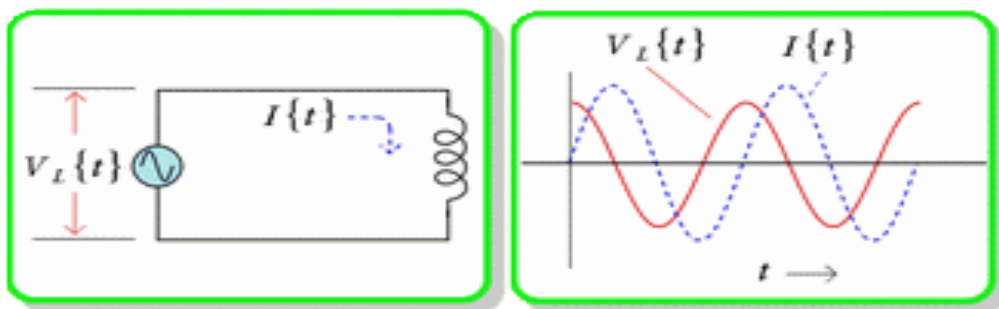
Reactance.

Reactance, in electricity, measure of the opposition that a circuit or a part of a circuit presents to electric current insofar as the current is varying or alternating. Steady electric currents flowing along conductors in one direction undergo opposition called electrical resistance, but no reactance. Reactance is present in addition to resistance when conductors carry alternating current. Reactance also occurs for short intervals when direct current is changing as it approaches or departs from steady flow, for example, when switches are closed or opened.

Reactance is of two types: **inductive and capacitive.**

Inductive reactance

Inductive reactance is associated with the magnetic field that surrounds a wire or a coil carrying a current. An alternating current in such a conductor, or inductor, sets up an alternating magnetic field that in turn affects the current in, and the voltage (potential difference) across, that part of the circuit. An inductor essentially opposes changes in current, making changes in the current lag behind those in the voltage. The current builds up as the driving voltage is already decreasing, tends to continue on at maximum value when the voltage is reversing its direction, falls off to zero as the voltage is increasing to maximum in the opposite direction, and reverses itself and

builds up in the same direction as the voltage even as the voltage is falling off again. Inductive reactance, a measure of this opposition to the current, is proportional to both the frequency f of the alternating current and a property of the inductor called inductance (symbolized by L and depending in turn on the inductor's dimensions, arrangement, and surrounding medium).

Inductive reactance XL equals 2π times the product of the frequency of the current and the inductance of the conductor,

simply $X_L = 2\pi f L$. Inductive reactance is expressed in ohms. (The unit of frequency is hertz, and that of inductance is henry.)

Capacitive reactance

Capacitive reactance, on the other hand, is associated with the changing electric field between two conducting surfaces (plates) separated from each other by an insulating medium. Such a set of conductors, a capacitor, essentially opposes changes in voltage, or potential difference, across its plates. A capacitor in a circuit retards current flow by causing the alternating voltage to lag behind the alternating current, a relationship in contrast to that caused by an inductor. The capacitive reactance, a measure of this opposition, is inversely proportional to the frequency f of the alternating current and to a property of the capacitor called capacitance (symbolized by C and depending on the capacitor's dimensions, arrangement, and insulating medium). The capacitive reactance XC equals the reciprocal of the product of 2π, the frequency of the current, and the capacitance of that part of the circuit, simply XC = 1/(2πfC). Capacitive reactance has units of ohms. (The unit of capacitance is farad.)
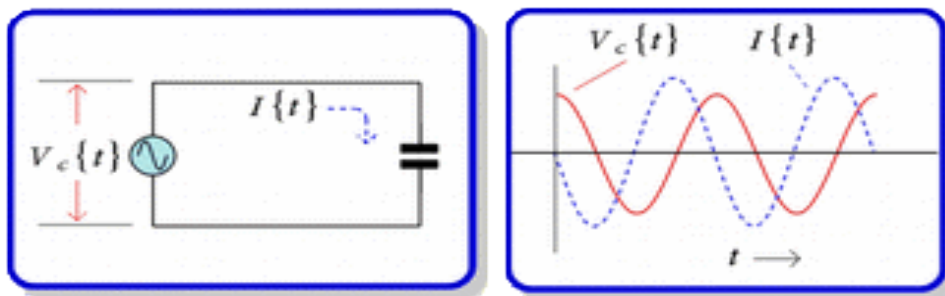
Because inductive reactance XL causes the voltage to lead the current and capacitive reactance XC causes the voltage to lag behind the current, total reactance X is their difference—that is, X = XL - XC. The reciprocal of the reactance, 1/X, is called the **susceptance** and is expressed in units of reciprocal ohm, called mho (ohm spelled backward).

Electrical Impendance

Electrical impedance (also called "impedance" in short) is an extension of the definition of resistance to alternating currents (AC). What is meant by this is that impedance includes both resistance (the opposition of the electric current that causes heat) and reactance (the measure of such an opposition as the current alternates) in detailing the opposition against electric currents. In direct currents (DC), electrical impedance is the same as resistance, but this does not hold true in AC circuits.
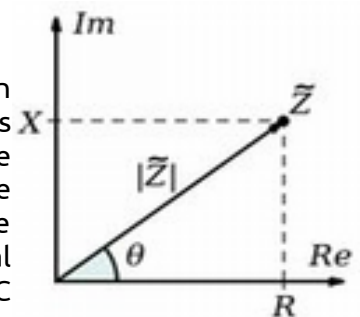
Impedance can also be different from resistance when a DC circuit changes flow in one manner or another, like the opening and closing of an electrical switch, as is observed in computers when they open and close switches to represent ones and zeros (binary language). The opposite of impedance is **admittance**, which is the measure of the allowance of current. The figure to the left is a complex impedance plane, in which impedance is represented by a Z, resistance is depicted as R, and reactance is depicted with X.

Why is Impedance Important?

Impedance and resistance both have applications that, believe it or not, exist in your own home. Your home electricity is controlled by a panel which has fuses in it. When you go through an electrical surge, the fuses are there to interrupt the power so that the damage is minimized. Your fuses are like very high-capacity resistors that will be able to take the blow. Without them, your house's electrical system would fry and you would have to build it up from scratch.This issue is solved thanks to impedance and resistance. Another situation in which impedance has

importance is in capacitors. In capacitors, impedance is used to control the flow of electricity in a circuit board. Without the capacitors controlling and regulating electrical flow, your electronics that use alternating currents will either fry or go berserk. Since alternating current delivers electricity at a fluctuating pulse, there needs to be a gate that holds back all the electricity and lets it go smoothly so that the electrical circuit is not overloaded or underloaded.

Power Factor

In AC circuits, the power factor is the ratio of the real power that is used to do work and the apparent power that is supplied to the circuit. The power factor can get values in the range of 0 to 1.

The power factor is equal to the real or true power P in watts (W) divided by the apparent power |S| in volt-ampere (VA):

$$PF = P(W) / |S(VA)|$$

PF - power factor.
P   - real power in watts (W).
|S| - apparent power - the magnitude of the complex power in volt·amps (VA).

Importance of Power Factor

A power factor of one or "unity power factor" is the goal of any electric utility company since if the power factor is less than one, they have to supply more current to the user for a given amount of power use. In so doing, they incur more line losses. They also must have larger capacity equipment in place than would be otherwise necessary.

Power factor correction
Power factor correction is an adjustment of the electrical circuit in order to change the power factor near 1. This will reduce the reactive power in the circuit and most of the power in the circuit will be real power. The power factor correction is usually done by adding capacitors to the load circuit, when the circuit has inductive components, like an electric motor.

Industrial facilities tend to have a "lagging power factor", where the current lags the voltage (like an inductor). This is primarily the result of having a lot of electric induction motors - the windings of motors act as inductors as seen by the power supply. Capacitors have the opposite effect and can compensate for the inductive motor windings. Some industrial sites will have large banks of capacitors strictly for the purpose of correcting the power factor back toward one to save on utility company charges.

Series and Parallel Circuits

There are two types of circuit we can make, called series and parallel. If there are no branches then it's a series circuit .If there are branches it's a parallel circuit

Resistance in series

A resistance series circuit is a circuit in which resistors are arranged in a chain, so the current has only one path to take. The current is the same through each resistor. The total resistance of the circuit is found by simply adding up the resistance values of the individual resistors:

equivalent resistance of resistors in series : R = R1 + R2 + R3 + ...
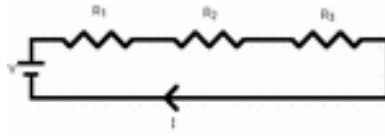
A series circuit is shown in the diagram above. The current flows through each resistor in turn. If the values of the three resistors are:
R1=8Ω, R2=5Ω and R3=7Ω, then the total resistance R=8+5+7 = 20Ω
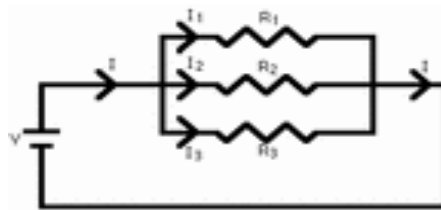
With a 10 V battery, by V = I R the total current in the circuit is:
I = V / R = 10 / 20 = 0.5 A. The current through each resistor would be 0.5 A.

Resistance in Parallel

A parallel resistance circuit is a circuit in which the resistors are arranged with their heads connected together, and their tails connected together. The current in a parallel circuit breaks up, with some flowing along each parallel branch and re-combining when the branches meet again. The voltage across each resistor in parallel is the same.

The total resistance of a set of resistors in parallel is found by adding up the reciprocals of the resistance values, and then taking the reciprocal of the total:

equivalent resistance of resistors in parallel: 1 / R = 1 / R1 + 1 / R2 + 1 / R3 +...

A parallel circuit is shown in the diagram above. In this case the current supplied by the battery splits up, and the amount going through each resistor depends on the resistance. If the values of the three resistors are:
R1=8Ω, R2=8Ω and R3=4Ω, Then Total resistance is found by

(1/R)= (1/8)+(1/8)+(1/4) =1/2 , So R=2Ω

With a 10 V battery, by V = I R the total current in the circuit is: I = V / R = 10 / 2 = 5 A.

The individual currents can also be found using I = V / R. The voltage across each resistor is 10 V, so:

I1 = 10 / 8 = 1.25 A
I2 = 10 / 8 = 1.25 A
I3=10 / 4 = 2.5 A

Note that the currents add together to 5A, the total current.

A parallel resistor short-cut

If the resistors in parallel are identical, it can be very easy to work out the equivalent resistance. In this case the equivalent resistance of N identical resistors is the resistance of one resistor divided by N, the number of resistors. So, two 40-ohm resistors in parallel are equivalent to one 20-ohm resistor; five 50-ohm resistors in parallel are equivalent to one 10-ohm resistor, etc.

When calculating the equivalent resistance of a set of parallel resistors, people often forget to flip the 1/R upside down, putting 1/5 of an ohm instead of 5 ohms, for instance. Here's a way to

check your answer. If you have two or more resistors in parallel, look for the one with the smallest resistance. The equivalent resistance will always be between the smallest resistance divided by the number of resistors, and the smallest resistance. Here's an example.

You have three resistors in parallel, with values 6 ohms, 9 ohms, and 18 ohms. The smallest resistance is 6 ohms, so the equivalent resistance must be between 2 ohms and 6 ohms (2 = 6 /3, where 3 is the number of resistors).

Doing the calculation gives 1/6 + 1/12 + 1/18 = 6/18. Flipping this upside down gives 18/6 = 3 ohms, which is certainly between 2 and 6.

Capacitor or Condensor

In a way, a capacitor is a little like a battery. Although they work in completely different ways, capacitors and batteries both store electrical energy. A capacitor is much simpler than a battery, as it can't produce new electrons -- it only stores them.

Inside the capacitor, the terminals connect to two metal plates separated by a non-conducting substance, or dielectric. You can easily make a capacitor from two pieces of aluminum foil and a piece of paper. It won't be a particularly good capacitor in terms of its storage capacity, but it will work.

In theory, the dielectric can be any non-conductive substance. However, for practical applications, specific materials are used that best suit the capacitor's function. Mica, ceramic, cellulose, porcelain, Mylar, Teflon and even air are some of the non-conductive materials used. The dielectric dictates what kind of capacitor it is and for what it is best suited. Depending on the size and type of dielectric, some capacitors are better for high frequency uses, while some are better for high voltage applications. Capacitors can be manufactured to serve any purpose, from the smallest plastic capacitor in your calculator, to an ultra capacitor that can power a commuter bus. NASA uses glass capacitors to help wake up the space shuttle's circuitry and help deploy space probes.
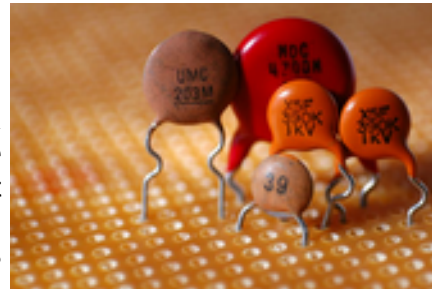
Farad

A capacitor's storage potential, or capacitance, is measured in units called farads. A1-farad capacitor can store one coulomb of charge at 1 volt. One amp represents a rate of electron flow of 1 coulomb of electrons per second, so a 1-farad capacitor can hold 1 amp-second of electrons at 1 volt.

A 1-farad capacitor would typically be pretty big. It might be as big as a 1-liter soda bottle, depending on the voltage it can handle. For this reason, capacitors are typically measured in microfarads (µf)

Applications

The difference between a capacitor and a battery is that a capacitor can dump its entire charge in a tiny fraction of a second, where a battery would take minutes to completely discharge. That's why the electronic flash on a camera uses a capacitor -- the battery charges up the flash's capacitor over several seconds, and then the capacitor dumps the full charge into the flash tube almost instantly. This can make a large, charged capacitor extremely dangerous -- flash units and TVs have warnings about opening them up for this reason. They contain big capacitors that can, potentially, kill you with the charge they contain.

Capacitors are used in several different ways in electronic circuits:
- Sometimes, capacitors are used to store charge for high-speed use. That's what a flash does. Big lasers use this technique as well to get very bright, instantaneous flashes.
- Capacitors can also eliminate ripples. If a line carrying DC voltage has ripples or spikes in it, a big capacitor can even out the voltage by absorbing the peaks and filling in the valleys.
- A capacitor can block DC voltage. If you hook a small capacitor to a battery, then no current will flow between the poles of the battery once the capacitor charges. However, any alternating current (AC) signal flows through a capacitor unimpeded. That's because the capacitor will charge and discharge as the alternating current fluctuates, making it appear that the alternating current is flowing.
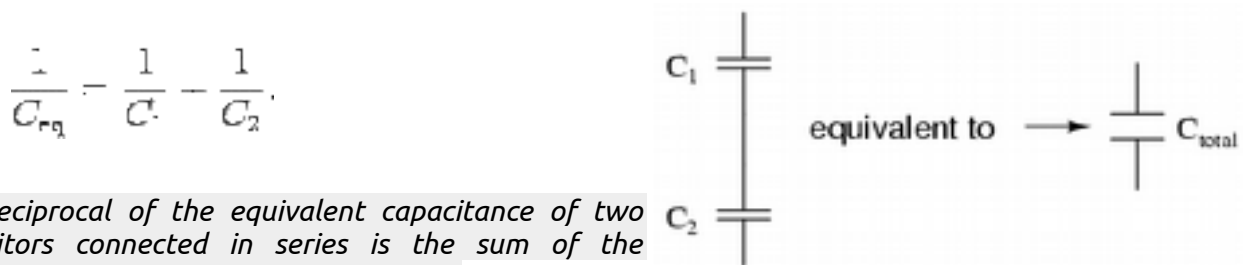
Capacitors in Series and in Parallel

Capacitors are one of the standard components in electronic circuits. Moreover, complicated combinations of capacitors often occur in practical circuits.

Capacitors in Series

When capacitors are connected in series, the total capacitance is less than any one of the series capacitors' individual capacitances. If two or more capacitors are connected in series, the overall effect is that of a single (equivalent) capacitor having the sum total of the plate spacings of the individual capacitors. As we've just seen, an increase in plate spacing, with all other factors unchanged, results in decreased capacitance.

Thus, the total capacitance is less than any one of the individual capacitors' capacitances. The formula for calculating the series total capacitance is the same form as for calculating parallel resistances:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} = \frac{1}{C_2},$$

The reciprocal of the equivalent capacitance of two capacitors connected in series is the sum of the reciprocals of the individual capacitances.

Capacitors in parallel

When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. If two or more capacitors are connected in parallel, the overall effect is that of a single equivalent capacitor having the sum total of the plate areas of the individual capacitors. As we've just seen, an increase in plate area, with all other factors unchanged, results in increased capacitance.

The reciprocal of the equivalent capacitance of two capacitors connected in series is the sum of the reciprocals of the individual capacitances.
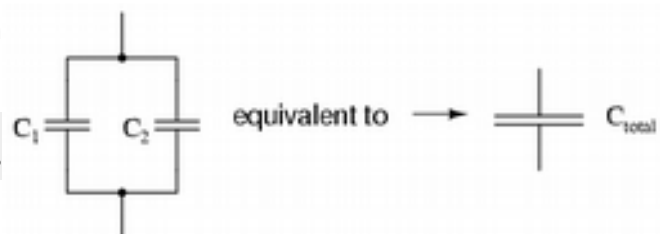
Thus, the total capacitance is more than any one of the individual capacitors' capacitances. The formula for calculating the parallel total capacitance is the same form as for calculating series resistances:

$$C_{eq} = C_1 + C_2,$$

Inductors

Inductors are passive devices used in electronic circuits to store energy in the form of a magnetic field. They are the compliment of capacitors, which store energy in the form of an electric field. An ideal inductor is the equivalent of a short circuit (0 ohms) for direct currents (DC), and presents an opposing force (reactance) to alternating currents (AC) that depends on the frequency of the current. The reactance (opposition to current flow) of an inductor is proportional to the frequency of the current flowing through it. Inductors are sometimes referred to as "coils" because most inductors are physically constructed of coiled sections of wire.

An inductor is characterized by its inductance, the ratio of the voltage to the rate of change of current, which has units of henries (H). Many inductors have a magnetic core made of iron or ferrite inside the coil, which serves to increase the magnetic field and thus the inductance. Along with capacitors and resistors, inductors are one of the three passive linear circuit elements that make up electric circuits. Inductors are widely used in alternating current (AC) electronic equipment, particularly in radio equipment. They are used to block the flow of AC current while allowing DC to pass; inductors designed for this purpose are called chokes. They are also used in electronic filters to separate signals of different frequencies, and in combination with capacitors to make tuned circuits, used to tune radio and TV receivers.

Series and parallel inductors

When inductors are connected in series, the total inductance is the sum of the individual inductors' inductances. To understand why this is so, consider the following: the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. If inductors are connected together in series (thus sharing the same current, and seeing the same rate of change in current), then the total voltage dropped as the result of a change in current will be additive with each inductor, creating a greater total voltage than either of the individual inductors alone. Greater voltage for the same rate of change in current means greater inductance.
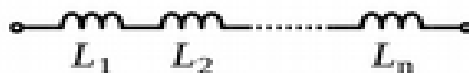
Thus, the total inductance for series inductors is more than any one of the individual inductors' inductances. The formula for calculating the series total inductance is the same form as for calculating series resistances:

$$L_{total} = L_1 + L_2 + \cdots + L_n$$

When inductors are connected in parallel, the total inductance is less than any one of the parallel inductors' inductances. Again, remember that the definitive measure of inductance is the amount of voltage dropped across an inductor for a given rate of current change through it. Since the current through each parallel inductor will be a fraction of the total current, and the voltage across each parallel inductor will be equal, a change in total current will result in less voltage dropped across the parallel array than for any one of the inductors considered separately. In other words, there will be less voltage dropped across parallel inductors for a given rate of change in current than for any of
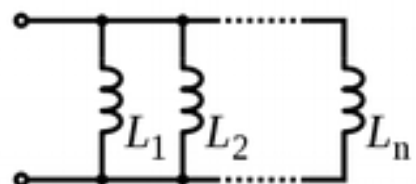
those inductors considered separately, because total current divides among parallel branches. Less voltage for the same rate of change in current means less inductance.

Thus, the total inductance is less than any one of the individual inductors' inductances. The formula for calculating the parallel total inductance is the same form as for calculating parallel resistances:

$$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}$$

Rectification.

Simply defined, rectification is the conversion of alternating current (AC) to direct current (DC). This involves a device that only allows one-way flow of electrons.

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as rectification. Physically, rectifiers take a number of forms, including vacuum tube diodes, mercury-arc valves, copper and selenium oxide rectifiers, semiconductor diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. Early radio receivers, called crystal radios, used a "cat's whisker" of fine wire pressing on a crystal of galena (lead sulfide) to serve as a point-contact rectifier or "crystal detector".

Use of Rectifiers

Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, detectors of radio signals serve as rectifiers.

The simple process of rectification produces a type of DC characterized by pulsating voltages and currents (although still unidirectional). Depending upon the type of end-use, this type of DC current may then be further modified into the type of relatively constant voltage DC characteristically produced by such sources as batteries and solar cells.

A more complex circuitry device which performs the opposite function, converting DC to AC, is known as an inverter.

Half-wave rectification

In half wave rectification of a single-phase supply, either the positive or negative half of the AC wave is passed, while the other half is blocked. Because only one half of the input waveform reaches the output, mean voltage is lower. Half-wave rectification requires a single diode in a single-phase supply, or three in a three-phase supply. Rectifiers yield a unidirectional but pulsating direct current; half-wave rectifiers produce far more ripple than full-wave rectifiers, and much more filtering is needed to eliminate harmonics of the AC frequency from the output.
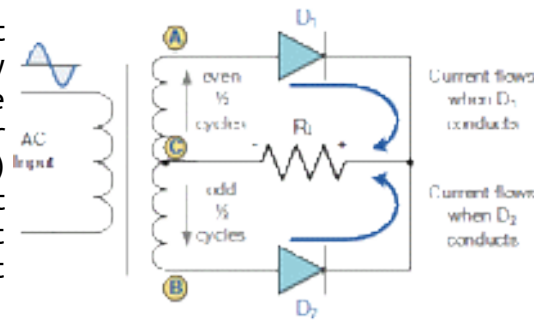

Half-wave rectifier
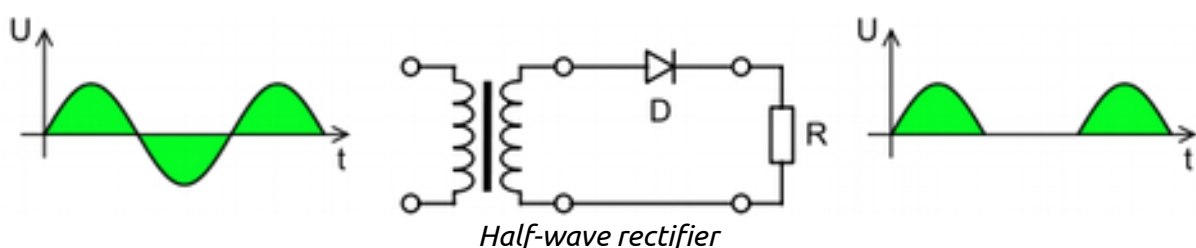
The no-load output DC voltage of an ideal half wave rectifier is

$$V_{dc} = \frac{V_{peak}}{\pi} \qquad V_{rms} = \frac{V_{peak}}{2}$$

V_{dc}, V_{av} - the DC or average output voltage,
V_{peak}, the peak value of the phase input voltages,
V_{rms}, the root-mean-square value of output voltage.

The Full Wave Rectifier

Like the half wave circuit, a full wave rectifier circuit produces an output voltage or current which is purely DC or has some specified DC component. Full wave rectifiers have some fundamental advantages over their half wave rectifier counterparts. The average (DC) output voltage is higher than for half wave, the output of the full wave rectifier has much less ripple than that of the half wave rectifier producing a smoother output waveform.

In a Full Wave Rectifier circuit two diodes are now used, one for each half of the cycle. A multiple winding transformer is used whose secondary winding is split equally into two halves with a common centre tapped connection, (C). This configuration results in each diode conducting in turn when its anode terminal is positive with respect to the transformer centre point C

Resultant Output Waveform

producing an output during both half-cycles, twice that for the half wave rectifier so it is 100% efficient as shown above
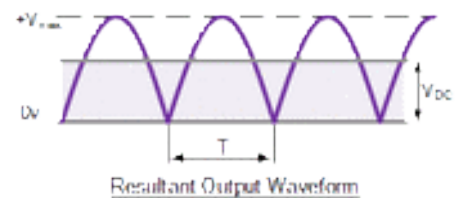
The full wave rectifier circuit consists of two power diodes connected to a single load resistance (RL) with each diode taking it in turn to supply current to the load. When point A of the transformer is positive with respect to point C, diode D1 conducts in the forward direction as indicated by the arrows. When point B is positive (in the negative half of the cycle) with respect to point C, diode D2 conducts in the forward direction and the current flowing through resistor R is in the same direction for both half-cycles. As the output voltage across the resistor R is the phasor sum of the two waveforms combined, this type of full wave rectifier circuit is also known as a "bi-phase" circuit.

As the spaces between each half-wave developed by each diode is now being filled in by the other diode the average DC output voltage across the load resistor is now double that of the single half-wave rectifier circuit and is about 0.637Vmax of the peak voltage, assuming no losses.

$$V_{dc} = \frac{2V_{max}}{\pi} = 0.637V_{max} - 0.9V_{RMS}$$

Where: V_{MAX} is the maximum peak value in one half of the secondary winding and V_{RMS} is the rms value.

The peak voltage of the output waveform is the same as before for the half-wave rectifier provided each half of the transformer windings have the same rms voltage value. To obtain a different DC voltage output different transformer ratios can be used. The main disadvantage of this type of full wave rectifier circuit is that a larger transformer for a given power output is required with two separate but identical secondary windings making this type of full wave

rectifying circuit costly compared to the "Full Wave Bridge Rectifier" circuit equivalent.

The Full Wave Bridge Rectifier

Another type of circuit that produces the same output waveform as the full wave rectifier circuit above, is that of the Full Wave Bridge Rectifier. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below.

Diode Bridge Rectifier

The four diodes labelled D1 to D4 are arranged in "series pairs" with only two diodes conducting current during each half cycle.
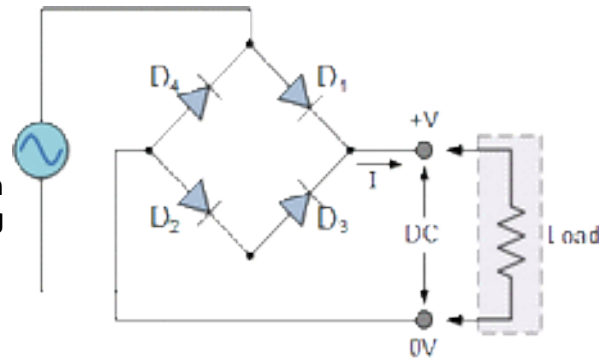
Positive Half-cycle Bridge

During the Positive half cycle of the supply, diodes D1 and D2 conduct in series, but diodes D3 and D4 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before.
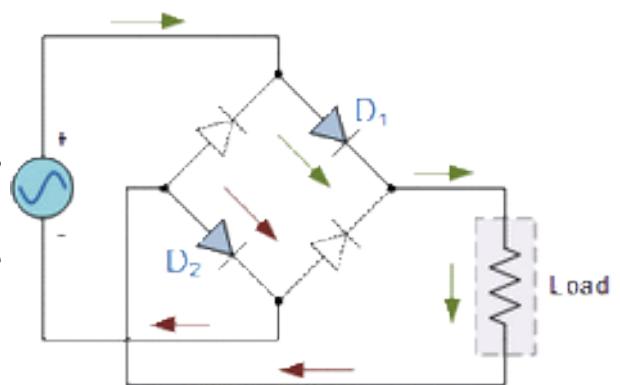
Negative Half-cycle Bridge

During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before.
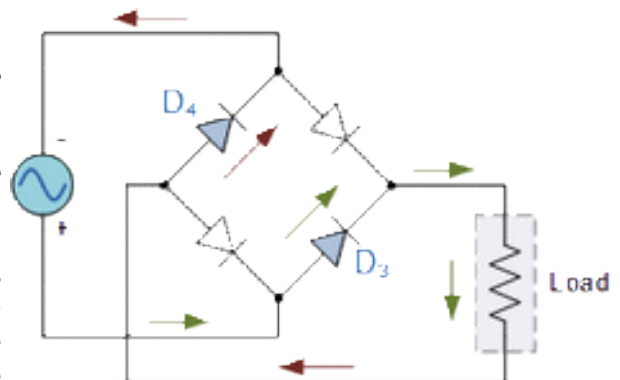
As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional the same as for the previous two diode full-wave rectifier, therefore the average DC voltage across the load is 0.637Vmax. However in reality, during each half cycle the current flows through two diodes instead of just one so the amplitude of the output voltage is two voltage drops (2 x 0.7 = 1.4V) less than the input VMAX amplitude. The ripple frequency is now twice the supply frequency (e.g. 100Hz for a 50Hz supply)

Although we can use four individual power diodes to make a full wave bridge rectifier, pre-made bridge rectifier components are available "off-the-shelf" in a range of different voltage and current sizes that can be soldered directly into a PCB circuit board or be connected by spade connectors.

The image to the right shows a typical single phase bridge rectifier with one corner cut off. This cut-off corner indicates that the terminal nearest to the corner is the positive or +ve output terminal or lead with the opposite (diagonal) lead being the negative or -ve output lead. The other two connecting leads are for the input alternating voltage from a transformer secondary winding.

The Smoothing Capacitor

We saw in the previous section that the single phase half-wave rectifier produces an output wave every half cycle and that it was not practical to use this type of circuit to produce a steady DC supply. The full-wave bridge rectifier however, gives us a greater mean DC value (0.637 Vmax) with less superimposed ripple while the output waveform is twice that of the frequency of the input supply frequency. We can therefore increase its average DC output level even higher by connecting a suitable smoothing capacitor across the output of the bridge circuit as shown below.

The smoothing capacitor converts the full-wave rippled output of the rectifier into a smooth DC output voltage. Generally for DC power supply circuits the smoothing capacitor is an Aluminium Electrolytic type that has a capacitance value of 100uF or more with repeated DC voltage pulses from the rectifier charging up the capacitor to peak voltage. However, their are two important parameters to consider when choosing a suitable smoothing capacitor and these are its Working Voltage, which must be higher than the no-load output value of the rectifier and its Capacitance Value, which determines the amount of ripple that will appear superimposed on top of the DC voltage.
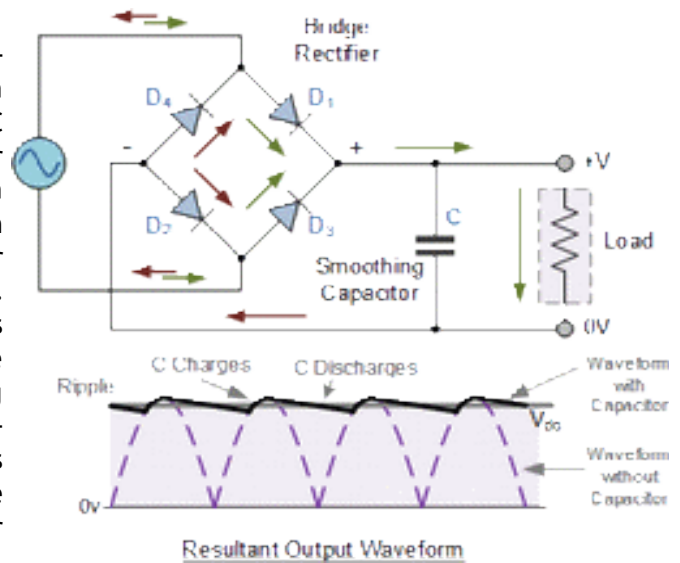
Too low a capacitance value and the capacitor has little effect on the output waveform. But if the smoothing capacitor is sufficiently large enough (parallel capacitors can be used) and the load current is not too large, the output voltage will be almost as smooth as pure DC.

Fig: A typical AC-DC adapter using a transformer,a bridge rectifier and a smoothing capacitor

Multiple choice questions

1. A _____ is a circuit element which takes energy from driving source and does not return it.
   a. capacitor
   b. resistor
   c. inductor
   d. diode

2. Example of an active device is
   a. electric bulb
   b. diode
   c. transformer
   d. loud speaker

3. A _____ is a circuit element that stores energy in a magnetic field and returns it.
   a. capacitor
   b. resistor
   c. zener diode
   d. inductor

4. A 100 F capacitor is required in an electronic circuit. Such a large value of capacitance is possible if the capacitor is a/an
   a. ceramic capacitor
   b. mica capacitor
   c. electrolytic capacitor
   d. paper capacitor

5. A resistor has a colour band sequence: brown, black, green and gold. Its value is
   a. 1 k ± 10%
   b. 1M ± 5%
   c. 10 k ± 5%
   d. 1 M ± 10%

6. A _____ is the circuit element that stores energy in an electric field and returns it.
   a. resistor
   b. inductor
   c. capacitor
   d. none of these

7. The colour bands on a fixed carbon resistor are brown, red, and black (given sequentially). Its value is
   a. 12
   b. 21
   c. 120
   d. 210

8. The term IC used in electronics denotes
   a. Indian culture
   b. integrated circuits
   c. internal combustion
   d. industrial control

9. Which one of the following is used as a passive component in electronic circuits?
   a. Vacuum triode
   b. transistor
   c. resistor

d. field effect transistor (FET)

10. What is the unit of measure for electrical pressure or electromotive force?
    a. amps
    b. ohms
    c. volts
    d. watts

Electrical pressure is the push given to electrons that causes them to flow through circuits. The unit of measure for electrical pressure is the volt.

11. Which of the following circuit configurations has the same amount of voltage drop across each of its components?
    a. parallel
    b. series-parallel
    c. series
    d. combination

In a series circuit, the current is equal at each point in the circuit and voltage is divided among the circuit components. In a parallel circuit, the voltage across each component is the same and the current is divided among the separate branches.

12. As temperature increases, what happens to the current-carrying ability of a wire?
    a. There is no change.
    b. The wire can carry more current.
    c. The wire can carry less current.
    d. The wire can carry no current.

Increasing temperatures cause electrons to be more active. The random nature of the increased activity causes collisions between thermally excited electrons and current carrying electrons. The collisions tend to disrupt the flow of electrons through the circuit. This disruption reduces the net current flow.

13. In a series circuit consisting of 3 resistors of 45 Ω each and a 50-V source, what is the approximate amount of heat produced?
    a. 16.6 W
    b. 18.5 W
    c. 135 W
    d. 150 W

Resistive elements in a circuit dissipate energy in the form of heat. Resistors connected in series are added to get total resistance. The power formula P = IE is used to determine the power used. First, use Ohm's law to find the current (I).
• I = E/R = 50/135 = 0.37 A
The power dissipated in heat can then be found using the power formula:
*• P = IE = 0.37 * 50 = 18.5 watts*

14. In a two-branch parallel circuit containing one 30-Ω resistor in each branch and powered from a 10-V source, what is the total current flowing in the circuit?
    a. 0.33 A
    b. 0.67 A
    c. 40 A
    d. 60 A

Because the voltage drop across each component of a parallel circuit is the same, Ohm's law can be used to find the current in each branch. The total current is then found by adding the current in each branch. Since in this case, the branches have equal resistance, simply find the current in one branch

and multiply by the number of branches.
• Current in one branch: I = E/R = 10/30 =0 .333A per branch
*• Total current of the parallel circuit: 0 .333 A * 2 branches =0 .67A*

15. Which of the following determines total power in a series circuit?
> **a.   source voltage times the current**
> b. total voltage applied to the circuit
> c. current flowing through a switch
> d. average of the wattage consumed by each resistor

> *The total power consumed in any circuit is a function of the power formula:*
> *• Power = current (I) times voltage (E) or P = IE*

16. If a resistor suddenly decreases in value (resistance decreases), what will happen to the current through the resistor?
> **a.   increases**
> b. remains unchanged
> c. decreases
> d. fluctuates

> *According to Ohm's law, I = E/R, current has an inverse relationship with resistance. As resistance (R) decreases, current (I) increases.*

17. What is the applied voltage on a circuit in which 0.5A is flowing and 10 W is generated?
> a. 2 V
> b. 5 V
> **c.   20 V**
> d. 50 V

> *Use the power formula, P = IE, to find this answer. Solving for E:*
> *• E = P/I = 10/0.5 = 20V*

18. What is the classification of an AC circuit in which the capacitive reactance is 50 Ω, the inductive reactance is 30 Ω and the resistance is 100 Ω?
> a. resistive
> b. inductive
> **c.   capacitive**
> d. resonant

> *In a reactive circuit, the higher value of reactance will determine whether the circuit is capacitive or inductive. Here, the capacitive reactance is higher than the inductive reactance. Therefore, the circuit is capacitive.*

19. When using a standard multimeter to measure AC voltage, what type of measurement will the multimeter indicate?
> a. peak-to-peak
> b. peak
> c. average
> **d.   RMS**

> *Electricity delivered to a wall outlet is stated in terms of RMS voltage. A standard multimeter provides a reading of AC voltage in terms of RMS.*

20. What happens to current flow in a capacitive circuit when the DC voltage across the capacitor is approximately equal to the source voltage?

        a. Current flow is optimized.
        b.   Little current flows.
        c. Current flow is maximum at the source.
        d. Current flow is maximum at the capacitor.

When a DC voltage is applied across a capacitor, there will be an initial flow of current. As the voltage across the capacitor charges up to the value of the source voltage, current flow will slowly decline. At the point where the voltage is approximately equal, all current in this circuit will stop flowing because there is no difference of potential

21. What is the term used to describe the ability of a device to store energy in the form of an electrical charge?

        a. inductance
        b. conductance
        c. reactance
        d. capacitance

A capacitor is a device that stores electrical energy

23. If the distance between the plates of a capacitor decreases while all other components of the capacitor remain the same, what happens to the capacitance of the device?

        a. increases
        b. remains the same
        c. decreases
        d. varies

The value of a capacitor (capacitance) can be increased by increasing the surface area of the plates, increasing the value of the dielectric constant, or decreasing the distance between the plates.

24. In mutual induction, what passes between conductors in order to create voltage?

        a. radiation
        b. magnetic flux
        c. current flow
        d. resistance

Magnetic flux is created as alternating current changes direction and causes lines of flux to vary in the magnetic field. As the lines of flux vary, they cause current to flow in nearby conductors

25. The Henry is the unit of measurement for which of the following properties?

        a. reactance
        b. capacitance
        c. resistance
        d. induction

26. Which of the following devices can be used to test the windings of an inductor for continuity?

        a. wattmeter
        b. voltmeter
        c. ohmmeter
        d. Wheatstone bridge

27. Which of the following circuit conditions does a metal oxide varistor (MOV) protect against?

        a. high voltage

b. high current
c. high circuit noise
d. high cross-talk

MOVs react very quickly to over-voltage conditions. When the voltage threshold of a MOV is exceeded, it instantly acts as a conductor, shorting the transient spike to ground. MOVs are commonly used to protect equipment that is attached to a transmission line.

28. How should a fuse be installed in a circuit to insure proper operation?
   a. parallel to the load
   b.   series with the load
   c. in any way possible
   d. at the ground point

   A fuse responds to an over-current condition by opening. This separates the source from the circuit in the event of an overload. Therefore it should be connected so that it is between the source of energy and the circuit—in series with the load.

29. In a parallel circuit operating with a source of 30 VAC, designed to carry a total current of 6 A, what happens to the protection device (fuse) when the resistance suddenly changes to 2 Ω?
   a. closes
   b. no change
   c. shorts to ground
   d.   opens

   A circuit designed to work with 30 volts at 6 amps has a load resistance of 5 Ω (Ohm's law). If the load resistance drops to 2 Ω, the circuit current will increase to 15 amps (Ohm's law) if there is no way to stop it. If the protection device (see question 21) works properly, it will open a circuit if current goes beyond its designed current carrying ability.

30. How many watts are in 100 microwatts?
   a. 0.01 milliwatts
   b.   0.1 milliwatts
   c. 1 milliwatts
   d. 10 nanowatts

   *100 microwatts = 100 * 10^{-6} watts = .0001 watts = 0.1 milliwatts.*

31. Which of the following is an appropriate use for a voltmeter?
   a.   To measure difference of potential
   b. To measure current flow
   c. To determine total resistance
   d. To determine power output

32. What should be observed when connecting a voltmeter into a DC circuit?
   a. rms
   b. resistance
   c.   polarity
   d. power factor

   Polarity is of major importance in direct current circuits. Voltmeters are sensitive to polarity when making measurements in DC circuits. Correct placement of leads is very important when making these kinds of measurements.

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