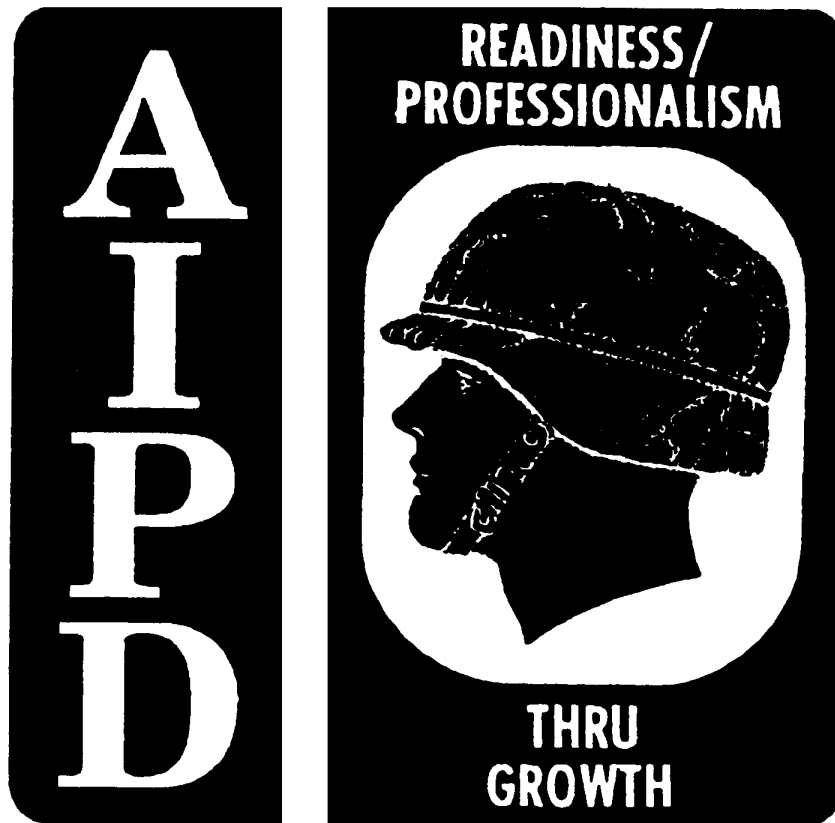


Fundamentals of Electricity Course

BASIC ELECTRICITY PART II

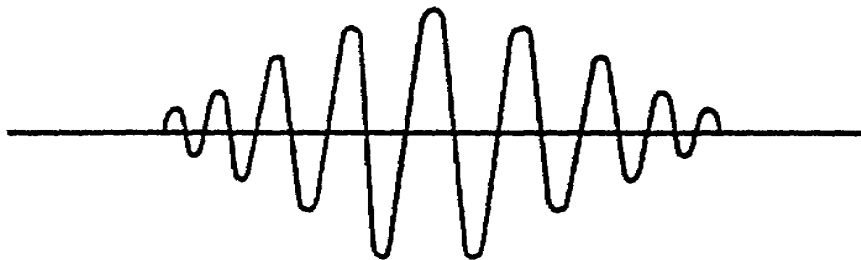


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BASIC ELECTRICITY PART II

Subcourse MM0704

Edition 7

Ordnance Missile and Munitions

United States Army Combined Arms Support Command

Fort Lee, Virginia 23801-1809

12 Credit Hours

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INTRODUCTION

This is the third of three subcourses on basic electricity. The first subcourse is a review of the mathematics necessary for the study of electricity. The second is on electron theory, magnetism, inductance capacitance, and alternating and direct currents. This subcourse is on resonance, filters, generators, motors, and transformers.

As a missile repairer, an understanding of basic electricity is a must for doing your job. Whether you are new to missile repair or have been in the field for awhile, the basics of this subcourse will help you sharpen your skills and increase your knowledge.

Supplementary Requirements

There are no supplementary requirements in material or personnel for this subcourse. You will need only this book and will work without supervision.

Credit Hours

Twelve credit hours will be awarded for the successful completion of this subcourse--a score of at least 70 on the end-of-subcourse examination.

Important: Electronic Examination Information

This paper subcourse does not contain the examination or examination response sheet. You must go to the following web site to complete the examination and submit it electronically for grading.

http://www.aimsrdl.atsc.army.mil/accp/accp_top.htm

Registered students (those with ACCP userids and passwords) should key in the userid and password to LOGON, then click on the EXAM button to access the examination.

Students who have not yet registered should click on the REGISTER button on the lower right corner of the screen. Follow directions to create a userid and password. Then click on the EXAM button to access the examination.

Lesson 1

RESONANCE AND TRANSIENCE

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to explain transience, waveforms, and time constants for charging and discharging resistive-inductive circuits. You will also be able to explain the meaning of resonance and the purpose, characteristics, operation, and use of series and parallel resonant circuits.

Conditions. You will have this subcourse book and work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 2, 3, and 4 (answer 23 of the 30 questions correctly).

INTRODUCTION

In the analysis of AC circuits in the previous subcourse, you learned the characteristics of inductive and capacitive reactance. When inductive and capacitive reactances are equal in magnitude, the circuit is said to be resonant. Since the resonant circuit is sensitive to differences in frequency, it becomes important in many electronic devices where frequency selection or rejection is required. Resonant circuits are used in electronics to determine the frequency of operation of transmitters and receivers; in radio to allow selection of stations broadcasting on different frequencies; and in telephone communication circuits to permit simultaneous transmission of dozens of conversations on a single line.

RESONANCE

Series

The series resonant circuit consists of capacitance and inductance in series. Resistances in the coil, condenser, generator, and wiring are generally represented as one resistor in this type of circuit. This combination is possible because resistances in series always add arithmetically.

The current and voltage conditions in a series resonant circuit are shown in figure 1-1 where equal inductive and capacitive reactances are represented. This is a resonant circuit. Generally, the series resistance of such a circuit is small compared with the reactance of the coil or the capacitor. In the circuit

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in the figure, there are only 5 Ω of resistance as compared with 200 Ω of inductive reactance and 200 Ω of capacitive reactance. To find impedance, use vector notation.

Z = total circuit opposition

R = resistance

X_C = capacitive reactance

X_L = inductive reactance

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{25 + (200 - 200)}$$

$$Z = \sqrt{25}$$

$$Z = 5$$

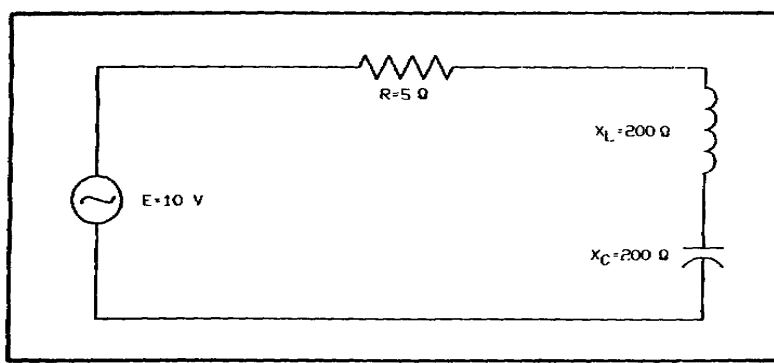


Figure 1-1. Series Resonant Circuit

Since the reactances are equal and opposite, they cancel out and the only opposition in the circuit is the resistance. The impedance of a series resonant circuit is, therefore, only the resistance in the circuit. To find the current do the following.

$$I_T = \frac{E_A}{Z} = \frac{10}{5} = 2 \text{ amps}$$

(I_T means total current.)

Note that the current of a series resonant circuit is in phase with the applied voltage. The power factor of the circuit is one.

A more interesting fact about the series resonant circuit is concerning the magnitude of the voltage across the coil and capacitor. The voltage across the coil (inductance) is

$$E_L = IX_L = (2) \times (200) = 400 \text{ V.}$$

The voltage across the capacitor is

$$E_C = IX_C = (2) \times (200) = 400 \text{ V..}$$

At first, it may seem impossible that such high voltages can exist across the coil and across the capacitor with only a small voltage applied. It is true, however, that such an increase in voltage can be obtained. The voltage across either reactance in this case is 40 times as great as the applied voltage, a voltage gain of 40. The voltage gain of any series resonant circuit is the ratio of the voltage across the coil (or condenser) to the applied voltage. Figure 1-2 shows a vector representation of this resonant circuit. Since E_L leads the applied voltage by 90° , and E_C lags the applied voltage by 90° , these two equal voltages are 180° out of phase with each other. (Recall E is EMF.) When added vectorially, they cancel. This means that the voltage across the series combination of the coil and capacitor is zero.

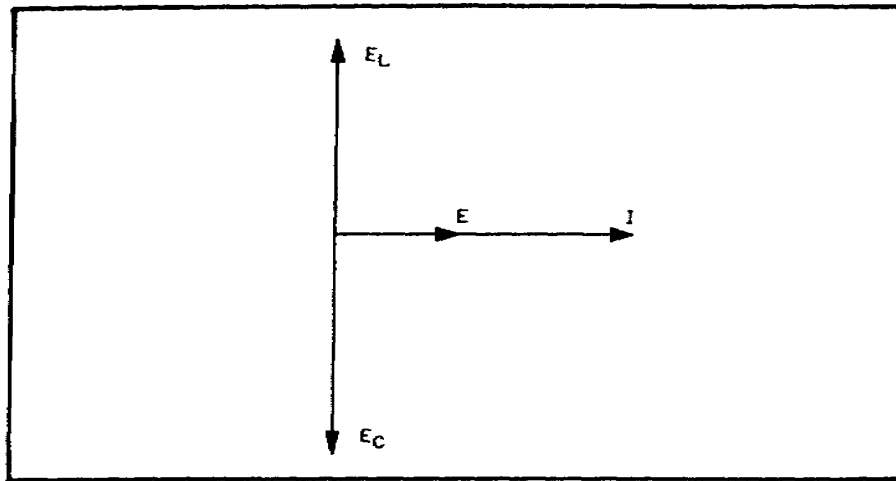


Figure 1-2. Vector Diagram of a Series Resonant Circuit.

Resonant Frequency Formula. For fixed values of L and C , there is only one frequency at which X_L equals X_C . This is true because X_C falls with an increase in frequency, while X_L rises with an increase in frequency. Figure 1-3 shows that their values can be numerically equal at only one point, which is the point at which the lines cross. Since the requirement for resonance is

$$X_L = X_C.$$

Resonance occurs when

$$2\pi fL = \frac{1}{2\pi fC}$$

Solving for f (frequency),

$$f^2 = \frac{1}{4\pi^2 LC}$$

and

$$f = \frac{1}{2\pi\sqrt{LC}},$$

which is the equation for frequency of resonance. All quantities in the equation are in basic units: Hertz, henrys, and farads.

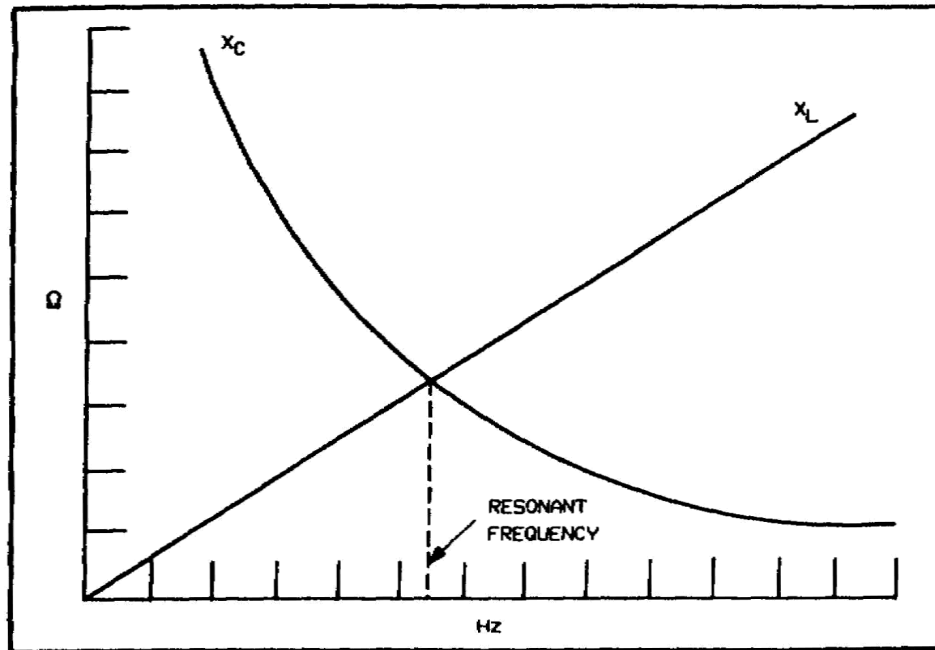


Figure 1-3. Reactance and Frequency.

Frequency and Current in an LCR Circuit (Circuit Containing Resistance, Inductance, and Capacitance). The important properties of the series LCR circuit arise because its impedance is lowest at the frequency of resonance ($Z = R$) and because it rises rapidly as the frequency is changed. When the applied frequency is below the circuit's resonant frequency, this impedance consists of resistance plus capacitive reactance. This is because X_C is larger than X_L . When the applied frequency is above the circuit's resonant frequency, X_L is larger than X_C , and the circuit impedance consists of resistance plus inductive reactance. The impedance curve of a series LCR circuit (R very small) is shown in figure 1-4A. Figure 1-4B shows the way current changes from leading to lagging as frequency increases.

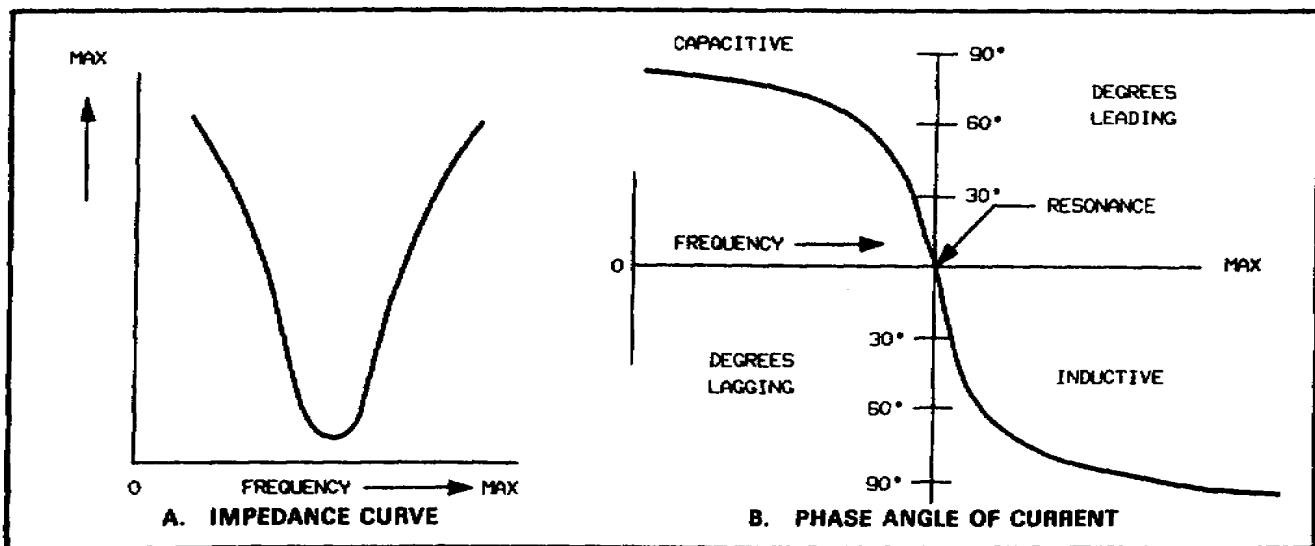


Figure 1-4. Series Resonance.

When the resistance in an LCR circuit is small, the circuit is very responsive to changes in frequency (figure 1-5). That is, the resonance curve is sharp and current at resonance is quite large, being limited only by R. If the resistance is large, in comparison with the reactance, the total impedance change as the frequency passes through resonance is small, the resonant peak is broad, and the current at resonance is quite small. A series resonant circuit with small resistance is said to have high gain Q (not to be confused with the Q of electric charge). Q is determined by the ratio

$$Q = \frac{P_A}{P_R} = \frac{I^2 X_L}{I^2 R} = \frac{X_L}{R}$$

(Q is the ratio of apparent power to real power.)

When the Q of a series resonant circuit is known, it may be used to enable an easy solution for the voltage across L or C at resonance. The voltage across either reactance by Ohm's Law is

$$E_L \text{ (or } E_C) = X_L I = (X_L) \frac{(E_{\text{applied}})}{R}$$

$$\text{But, since } Q = \frac{X_L}{R}, E_L = QE_{\text{applied}}.$$

This is the phenomenon of resonance, that is, the applied voltage is multiplied by the Q gives the voltage across the coil or capacitor.

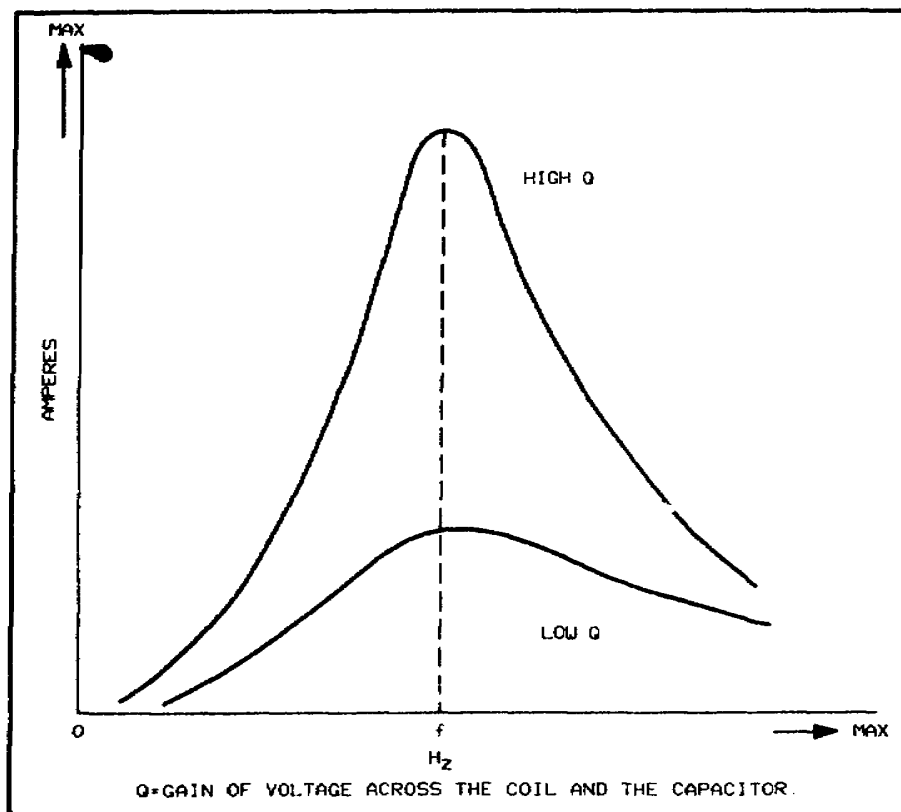


Figure 1-5. Resistance in an LCR Circuit.

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Bandwidth. Sharpness of resonance is difficult to define since there is no exact point on the curve that can be designated as the limit of the bandpass. However, because it is often necessary to state the band of frequencies that a resonant circuit will pass, an arbitrary standard has been set up. The limiting frequencies are those at either side of resonance at which the current falls to 0.707 of the current at resonance. These are known as the half power points (A and B, fig 1-6). The circuit shown in figure 1-6 has a bandwidth of 1,000 Hz between half power points. The bandpass is from 1,000 Hz to 2,000 Hz.

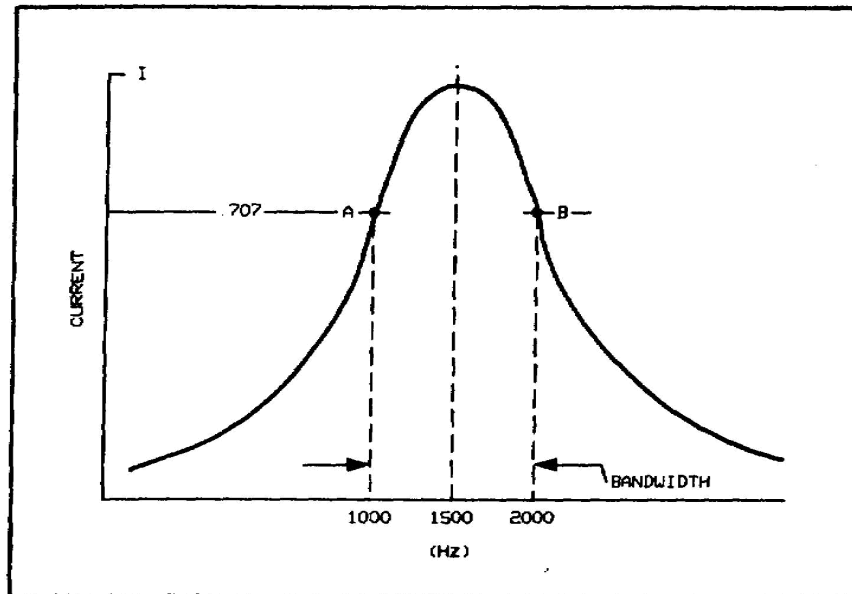


Figure 1-6. Band Pass of a Series Resonant Circuit.

In this circuit, 0.707 is equivalent to half power. This is because, in any circuit, power is proportional to I^2 . The power at resonance is I^2R . At the half power point, the current is less. Call it I_1 . Then,

$$I_1^2 R = \frac{I^2 R}{2},$$

$$I_1^2 = \frac{I^2}{2},$$

$$I_1 = \frac{I}{\sqrt{2}},$$

$$I_1 = 0.707 \times I.$$

Therefore, the current at the half power point is 0.707 times the current at the resonant peak.

Some Uses for Series Resonant Circuits. The resonant rise of voltage in the series LCR circuit is valuable in giving selectivity to radar and radio receivers. The reason for this is that, with a high Q circuit, the feeble signal voltages with the desired frequency can be increased tremendously, while there is little gain in voltage at adjacent frequencies.

A recent development in television is the use of high Q series resonant circuit for developing voltages of the order of 70 kV for high intensity, projection-type tubes.

Most resonant radio frequency circuits are made with a variable element so that the frequency of resonance may be adjusted. A radio receiver, for example, contains several adjustable resonant circuits. Probably the most common means of adjustment is the variable capacitor. Since the development of the powdered iron core, variation of inductance has also become simple and popular. At high frequencies, such coils are sometimes resonated with their distributed capacitance and that of the associated wiring. Using the equation for the frequency of resonance,

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

you can see that decreasing L, C, or both, results in an increased resonant frequency.

Parallel

The simplest parallel resonant circuit is inductance and capacitance in parallel, connected to a generator as shown in figure 1-7. For simplicity, assume that there is no resistance in L or C. The frequency is such that $X_L = X_C$. The currents through the two branches are then equal.

$$I_L = I_C, \text{ or } I_L - I_C = 0$$

or vectorially,

$$jI_L - jI_C = 0.$$

Adding these currents to find the total current shows their vector sum to be zero. Since no current is drawn from the generator, this theoretically perfect resonant circuit has infinite impedance. This is directly opposite to the condition of series resonance. The requirement that $X_L = X_C$ is, of course, the same as that of the series resonant circuit. Because of this, the equation for frequency of resonance,

$$f = \frac{1}{2\pi\sqrt{LC}},$$

is the same for both series and parallel circuits.

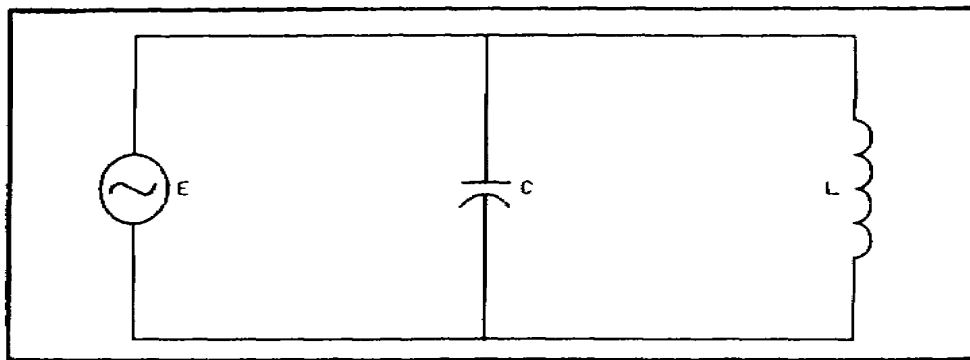


Figure 1-7. Parallel Resonant Circuit.

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In any practical parallel LC circuit, there is always some resistance in the branches, mainly in the inductive branch is the resistance of the coil winding (distributive resistance). This means that the current through the inductive branch will lag the applied voltage by slightly less than 90° . The currents through the two branches do not cancel entirely, so there is some total current. This line current furnished by the generator is very small. A circuit that draws only a small amount of current has a high impedance.

When the frequency of the applied voltage in a parallel circuit is such that substituting the values of L, C, and f in the formula results in an equality, a resonant condition exists. If L, C, or f is then changed, the circuit is off resonance, the current is increased, the impedance is decreased, the reactances are unequal, and the frequency formula is no longer usable.

The above facts apply to parallel resonant circuits where the resistance in series with the capacitor is insignificant, and the Q of the coil is high.

Power in the Parallel Resonant Circuit. If the circuit is known to be resonant, total power dissipated may be calculated by

$$P = EI.$$

Whether the circuit is resonant or nonresonant, total power is equal to the sum of the power dissipated in each resistance. Power dissipated in a circuit using a high Q coil and a condenser free of losses will be very small.

The energy lost in a parallel resonant circuit is mainly due to resistance in the windings of the coil, although, at very high frequencies, losses also become apparent in the capacitor. Series resistance in the inductive or capacitive branch is carefully kept to a minimum, since the smaller the series R, the smaller the I^2R loss. Any resistance across the tuned circuit (which is sometimes unavoidable) should be kept as large as possible; because the power lost is proportional to E^2/R . As with the series circuit, large losses make the resonance curve nonselective.

Resonance Frequency Curves. The resonant curve for the parallel circuit is shown in figure 1-8A. It is plotted for impedance versus frequency and is similar to the current versus frequency curve of the series resonant circuit

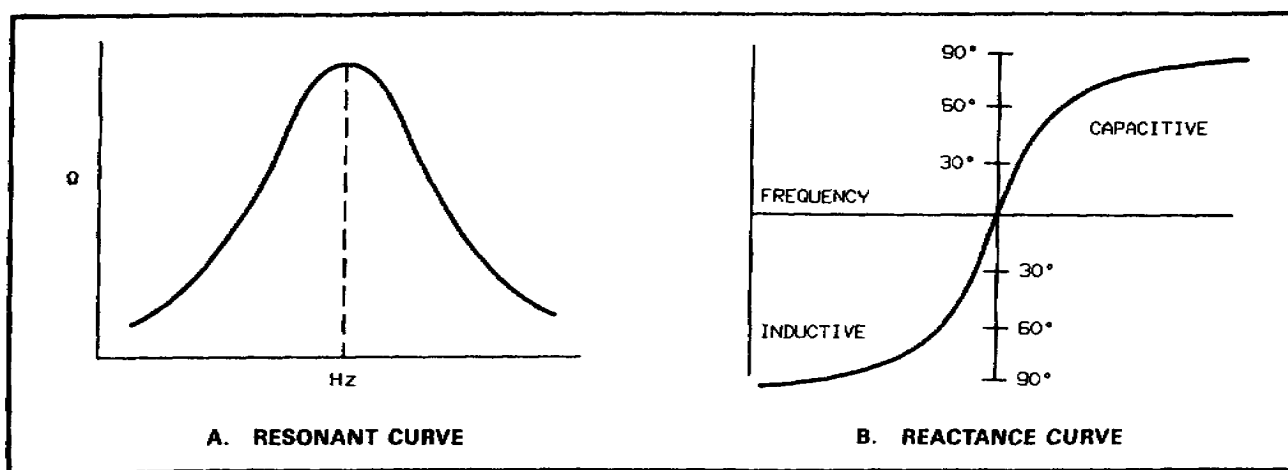


Figure 1-8. Parallel Resonance Frequency Curves.

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The reactance curve (figure 1-8B) shows that, for applied frequencies below the circuit's resonant frequency, the circuit is inductive, while above resonance, it is capacitive. To decide what kind of reactance is presented when the applied frequency is above the resonant frequency, think in terms of the total current drawn. Is it leading or lagging current? Since the parallel LC circuit offers a very high impedance at resonance, it is of primary importance where a relatively large voltage change is desired as the circuit approaches resonance. It is, therefore, desirable to use a generator of high internal impedance. In figure 1-9, R is the internal impedance of the generator. If R is very small, then change in the current drawn by the LC circuit produces little change in the voltage drop across R , and the voltage across LC remains practically constant as the circuit is varied through resonance. If R is large, any change in current produces large changes in voltage across R and results in large voltage changes across the resonant circuit.

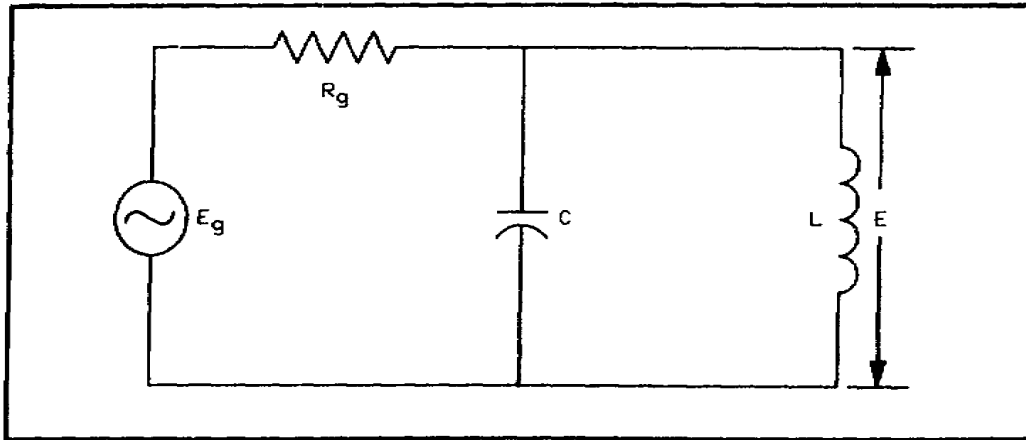


Figure 1-9. Parallel Resonant Circuit with Generator (R).

The voltage curves for a parallel resonant circuit are shown in figure 1-10 for both high and low generator impedance. Unlike the series resonant circuit, note that increasing the R of the generator improves the selectivity of the circuit

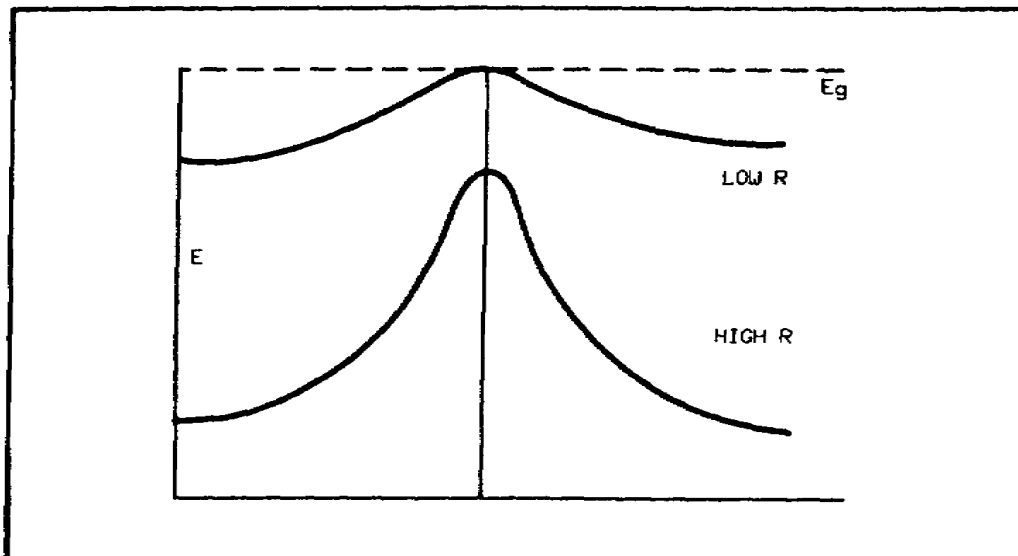


Figure 1-10. Voltage Curves for Parallel Resonant Circuit

Uses of Parallel Resonant Circuits. Since the parallel resonant circuit has a high impedance, it is often useful for rejecting undesired frequencies. An example is the wave trap, figure 1-11, which is used to reject an undesired signal from a receiver. It consists of a parallel resonant circuit in series with the antenna of the receiver and tuned to the interfering frequency.

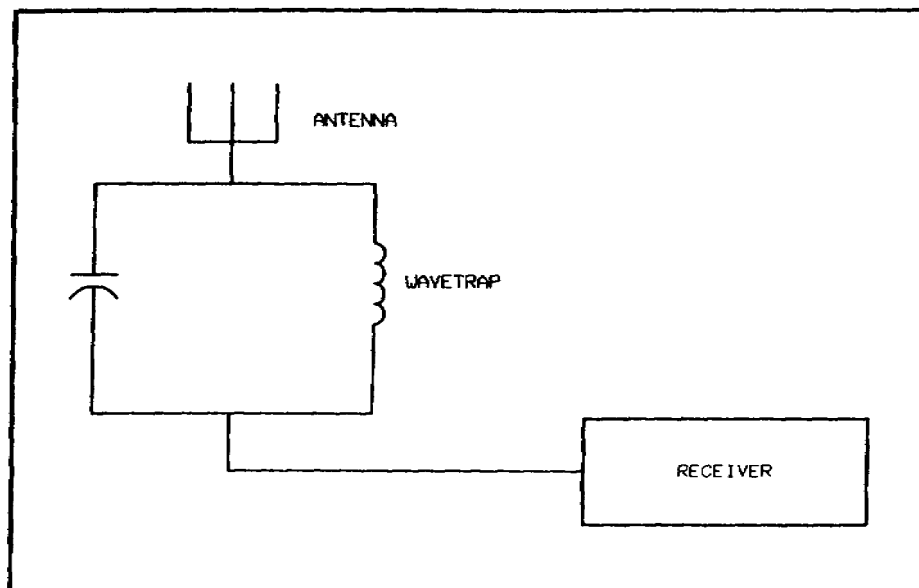


Figure 1-11. Parallel Resonant Circuit Used as Wave Trap.

Another function of the parallel resonant circuit is that of determining the frequency of operation of radio and radar transmitters. The parallel resonant circuit lends itself very well to vacuum tube generators, which have a high internal impedance.

Table 1-1. Comparison of Series and Parallel Resonance.

<i>Characteristic</i>	<i>Series</i>	<i>Parallel</i>
Impedance at resonance	Minimum	Maximum
Power factors at resonance	Unity	Unity
Equation for frequency at resonance	$f = \frac{1}{2 \pi \sqrt{LC}}$	$f = \frac{1}{2 \pi \sqrt{LC}}$
Desirable source (generator) impedance	Low	High
Bandpass	Frequencies between half power points	Frequencies between half power points
Reactance, source frequency below resonance	Capacitive	Inductive
Reactance, source frequency above resonance	Inductive	Capacitive

Mechanical Analogies

Many electrical principles can be better understood when they are compared to mechanical devices. A device closely related to the resonant circuit is the pendulum. As in the case of a free-swinging pendulum, the frequency of the resonant circuit is practically independent of the amplitude of the force applied and there is but a single resonant frequency. However, both reach large amplitudes with very small amounts of power applied, both can be made to oscillate with a push along a small part of each cycle, and both continue to oscillate for many cycles after the driving force has been removed.

The only energy required to keep a pendulum going is friction. A large amount of energy is stored in the moving pendulum in two forms: kinetic energy when the pendulum falls and potential energy as the pendulum rises. A similar continuous exchange of energy goes on in the resonant circuit. Imagine a capacitor connected across an inductor. Assume the capacitor is to be charged by some outside force that is no longer active (a generator that has just been disconnected). Energy is stored in the electrostatic field of the capacitor, which must discharge through the coil. This takes time because the inductor opposes a change in current. As the capacitor discharges, its energy is stored in the magnetic field built up by the flow of current in the coil. When the voltage across the capacitor is gone, current continues to flow in the same direction because of the collapse of the magnetic field about the coil. This current charges the capacitor and current flows in the opposite direction for a half cycle. Except for resistance losses, which convert this circulating energy into heat, it could be made to oscillate forever from a single pulse of electrical energy. In practice, these oscillations are not detectable after a few hundred cycles; the exact rate of dying out (damping) is determined by the Q of the circuit. As with the pendulum, the only energy required by the resonant circuit is that amount that is wasted by the electrical equivalent of friction, which is resistance.

Summary of Series and Parallel Resonance

Series resonant circuits have in common the following:

- The current is maximum at resonance.
- $X_L = X_C$ at resonance.
- Power factor is one (unity) at resonance.
- When the applied voltage is below the resonant frequency of the LC circuit, the circuit reactance is capacitive.
- When the applied voltage is above the resonant frequency of the LC circuit, the circuit reactance is inductive.
- Frequency of resonance equals $\frac{1}{2\pi \sqrt{LC}}$.

Parallel resonant circuits have in common the following:

- The impedance is maximum at resonance.
- $X_L = X_C$ at resonance.
- Power factor is one at resonance.

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- When the applied voltage is below the resonant frequency of the LC circuit, the circuit reactance is inductive.
- When the applied voltage is above the resonant frequency of the LC circuit, the circuit reactance is capacitive.
- Frequency of resonance equals $\frac{1}{2\pi\sqrt{LC}}$ (where R is negligible).

TRANSCIENCE

Time Constants and Transience

Transience is that period during which there is a rapid change from one steady state to another. An example is the current through a capacitor after a voltage is applied to it.

The study of time constants concerns itself chiefly with the study of any electric circuit during its DC transient periods. Although a square wave may be AC, each half cycle may be considered a temporary DC voltage. Time constants involve nonsinusoidal waves such as square waves, triangular waves, and spiked waves.

In the study of circuits it is vital to know how the size of capacitors, resistors, and inductors, along with the frequency, will determine the rate of the change in the transient wave.

Review of Simple Circuits

Review the following before starting the detailed explanation of time constants.

The R Circuit. The expression for the voltage across a resistor is

$$E_L = IX_L,$$

The resistance (R) is the factor that, if multiplied by the current (I), establishes the voltage across a resistance.

The L Circuit. The expression for the voltage across an inductor is

$$E_L = IX_L,$$

$$\text{where } X_L = 2\pi fL.$$

The C Circuit. The expression for the voltage across a capacitor is

$$E_C = IX_C,$$

$$\text{where } X_C = \frac{1}{2\pi fC}.$$

Time Constants

The RC Circuit. The expression for the sum of the voltage drops of the circuit shown in figure 1-12 is

$$E_A = \sqrt{E_R^2 + E_C^2},$$

where the voltage across the resistor is proportional to the current through it, and the voltage across the capacitor is proportional to the capacitive reactance, X_C .

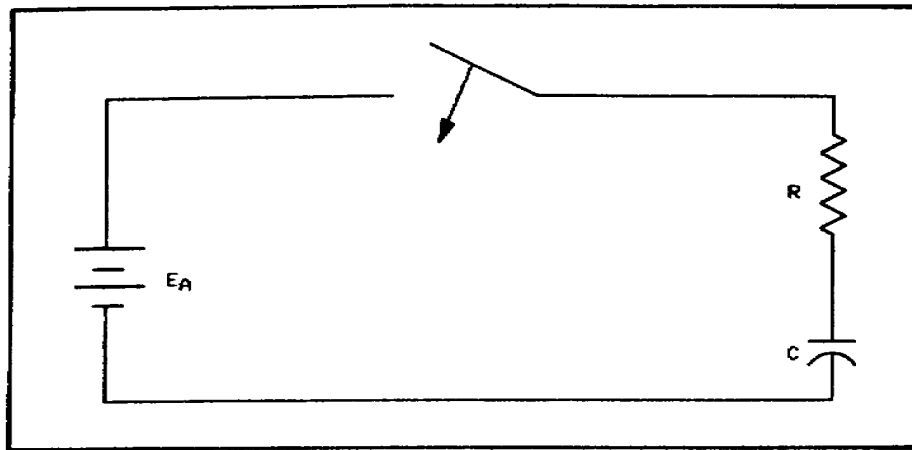


Figure 1-12. RC Circuit.

The instant the switch is closed, in figure 1-12, the voltage across the capacitor is zero and the voltage across the resistor is E_A . After a period of time, the transient action will be complete, the capacitor voltage will be E_A , and the resistor voltage will be zero. Figure 1-13 shows the relative values of resistor voltage and capacitor voltage as time elapses.

RC Time Constants. The value of C determines the amount of electron displacement required for a given voltage, and the value of R determines the rate of electron displacement. Therefore, the time from T_0 to T_1 , in figure 1-13, is determined by the value of R and C in the circuit. The time constant of the RC circuits is the length of time required for the capacitor to charge to 63.2 percent of the applied voltage. In other words, at T_1 the capacitor charge has reached 63.2 percent of its final charge.

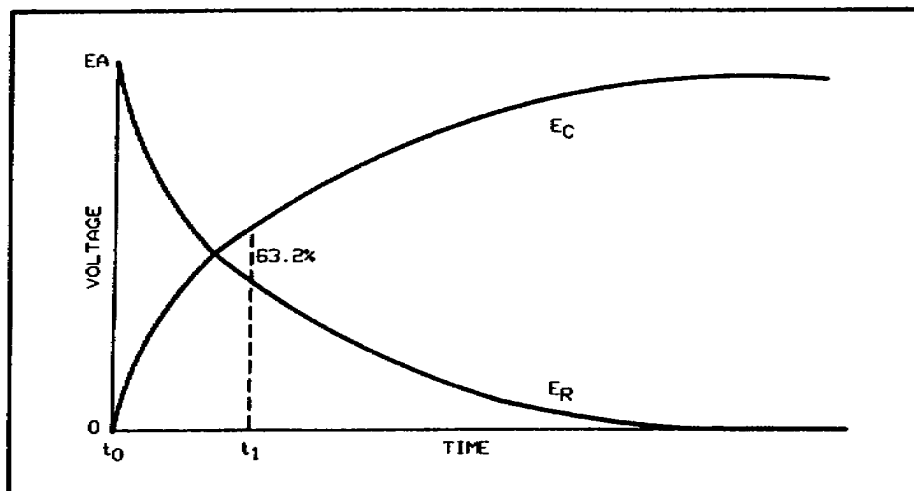


Figure 1-13. Voltages in the RC Circuit During the Charging Period.

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As an example of the time constant, let the voltage across the capacitor in figure 1-14A be represented by the graph in figure 1-14B.

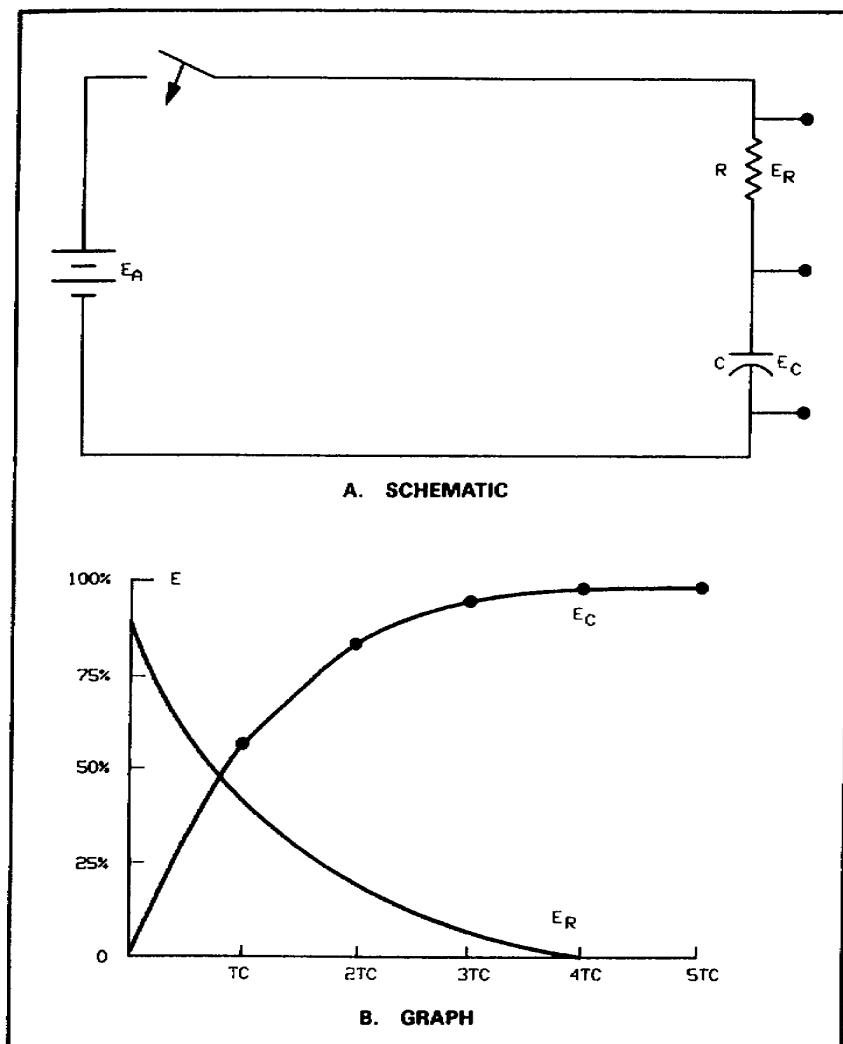


Figure 1-14. RC Time Constant.

When $t = TC$ (one time constant), $E_C = 63.2$ percent of E .

When $t = 2TC$ s (two time constants), $E_C = 63.2$ percent of $E + 63.2$ percent of the remaining applied voltage after one time constant. That equals $0.632E + 63.2$ percent of $0.368E$ which is 86.5 percent of E .

When $t = 3TC$ s (three time constants), the capacitor will have acquired another 63.2 percent of the remaining applied voltage or 95.1 percent of E .

When $t = 4TC$ s, $E = 98.2$ percent of E and after $5 TC$ s, $E_C = 99.3$ percent of E . Thus, for practical purposes, the capacitor may be considered fully

charged after five time constants. In other words, when $t = 5TCs$, the transient action is complete. One steady state has been altered and is now settled into another steady state: transience. From this, you can see that the value of R and C determines the time required to charge the capacitor. Remember that the product of R and C is referred to as a time constant, and this product is a measure of time as follows:

$$R (\Omega) \times C (fd) = \text{time constants (sec)},$$

$$R (M\Omega) \times C (\mu fd) = \text{time constants (sec)},$$

$$R (\Omega) \times C (\mu fd) = \text{time constants } (\mu sec).$$

The last equation above is the one most commonly used in electronics.

Discharging a Capacitor Through a Resistor. If a charged capacitor is placed across a resistor as illustrated in figure 1-15A, the capacitor will begin to discharge. During discharge, the capacitor voltage and resistor voltage is the same ($E_C = E_R$). At the first instant, the voltage is 100 V and the current through meter A is 10 mamps. After 1 TC, ($R \times C = 10^3 \times .1 = 1,000 \mu sec$) the voltage is 36.8 V and the current is 3.68 mamps (63.2 percent change). See figure 1-15B.

After 2 TCs, 2,000 μsec , the voltage is 13.5 V and the current is 1.35 mamps (another 63.2 percent change, 86.5 percent total change). See figure 1-15C. After 3 TCs, 3,000 μsec , the voltage is 4.9 V and the current is 0.49 mamps. After 4 TCs, $E = 1.8$; after 5 TCs, $E = 0.0$, and for all practical purposes, the capacitor is discharged and the current is zero.

Universal Time Constant Graph. Thus far, it is possible to find the resistor and capacitor voltage and the current in a series RC circuit with direct current applied for any whole number of time constants. Suppose, however, you want to know this information for a fractional number of time constants. For example, use the circuit shown in figure 1-16 and find the E_C , E_R , and I after 1,500 μsec (1.5 TC).

You know that E_C is 63.2 V after 1,000 μsec (1 TC) and 86.5 V after 2,000 μsec (2 TCs). Remembering that the capacitor does not charge at a linear rate,

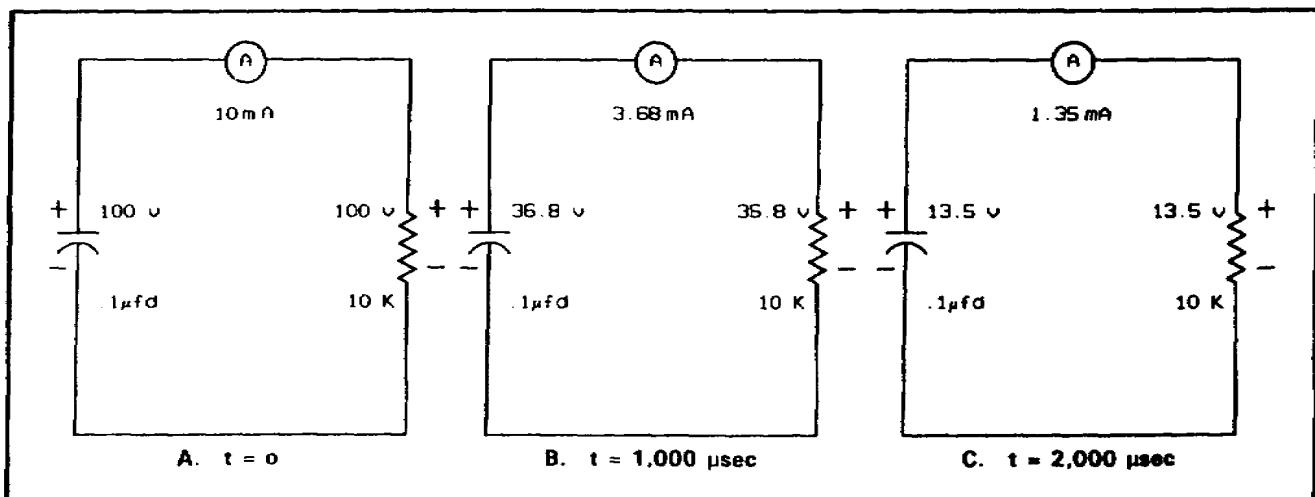


Figure 1-15. Discharging a Capacitor.

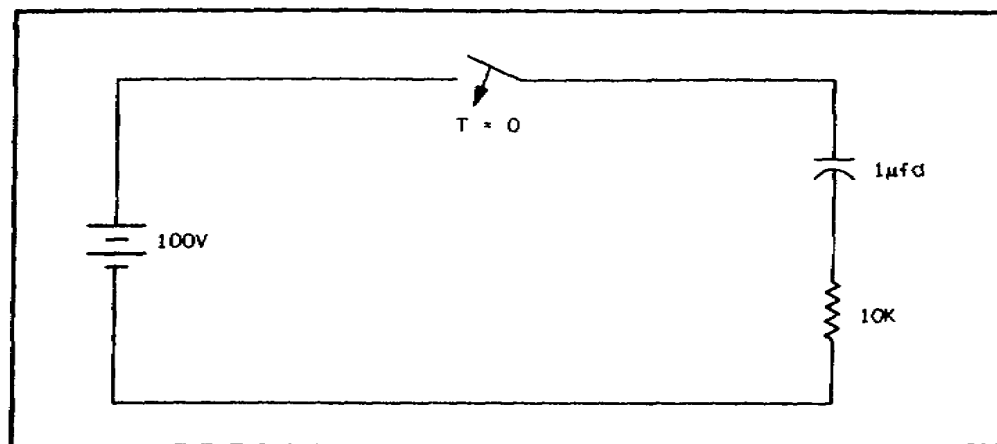


Figure 1-16. Series RC Circuit.

you cannot assume that the voltage will be midway between the 63.2 V and 86.5 V (74.8 V) at 1.5 TCs. Hence, some arrangement must be made to show all the intermediate situations between whole time constants.

At any time, the voltage and current of any component can be calculated mathematically by the use of calculus. It can also be done more simply by plotting a graph of the percentage of change using values for each whole time constant. See figure 1-17. The first instant that voltage is applied to a series RC circuit (zero time constant), the percentage of applied voltage across the capacitor is zero. This is point A on the graph. One time constant after the voltage is applied, 63.2 percent of the applied voltage, appears across the capacitor. This is point B on the graph. After 2 TCs, the applied voltage across the capacitor has risen to 86.5 percent of the applied voltage. This is point C. The voltage across the capacitor after 3 TCs is 95.1 percent (point D); after 4 TCs, 98.2 percent (point E); and after 5 TCs, 99.3 percent (point F).

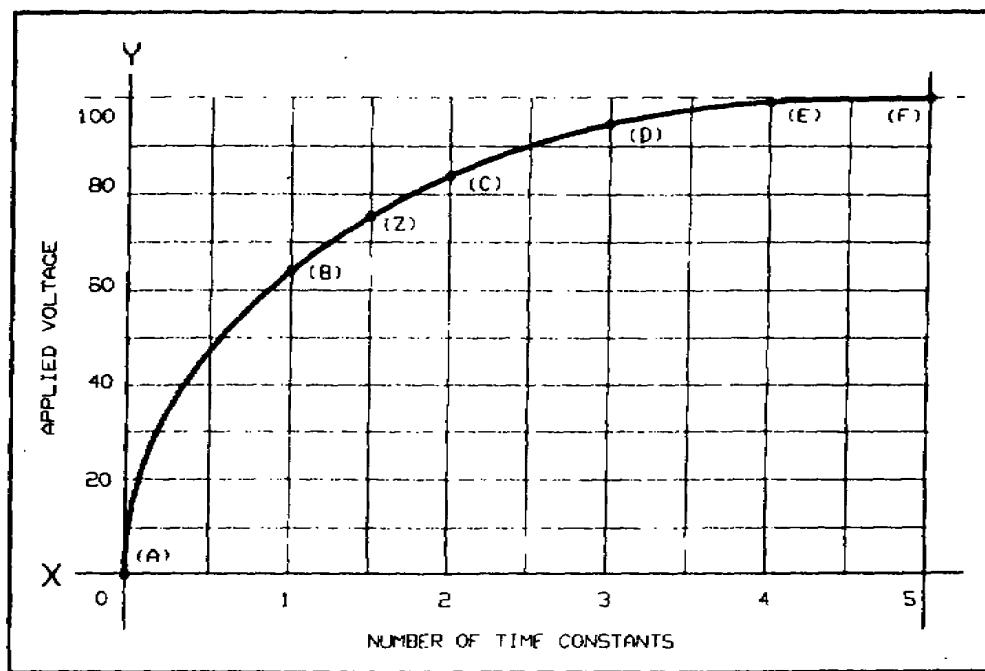


Figure 1-17. Percent of Capacitor Voltage.

A smooth curve connecting points A through F follows the capacitor charge and shows all the intermediate percentages of the applied voltage found across the capacitor at both whole and fractional time constants.

You can find the voltage across the capacitor for 1.5 TCs on the graph. On the X axis find 1.5 TCs. From this point move vertically up to the curve for the capacitor charge. Call this point Z. Now, move horizontally from point Z to the Y axis where the percentage of applied voltage to which the capacitor has charged is given. The capacitor will have charged to 78 percent of the applied voltage. Since the applied voltage in the circuit of figure 1-16 is 100 V, the voltage across the capacitor for 1.5 TCs is $0.78 \times 100\text{V} = 78\text{V}$.

You can also find the voltage across a capacitor after any number of time constants. You can find the number of time constants in any given time by dividing the product of $R \times C$ into the time, thus,

$$\text{Number of TCs} = \frac{t}{RC}$$

Figure 1-18 is a more accurate graph than the one in figure 1-17. It is used for computations in series RC circuits. Known as a Universal Time Constant Chart, you can use it to determine E_C , E_R , and I as accurately as possible without calculations. This chart, in addition to being accurate, provides curves for the capacitor voltage on charge (curve A), and also for the resistor voltage on charge (curve B). On the graph of figure 1-18, you can also use curve B to determine the capacitor discharge voltage and curve A the resistor voltage on discharge.

On the chart, the numbers 1 through 5 along the horizontal axis represent the number of time constants rather than specific units of time. This means the graph can be used for computations in any series RC circuit regardless of the length of time represented by each time constant.

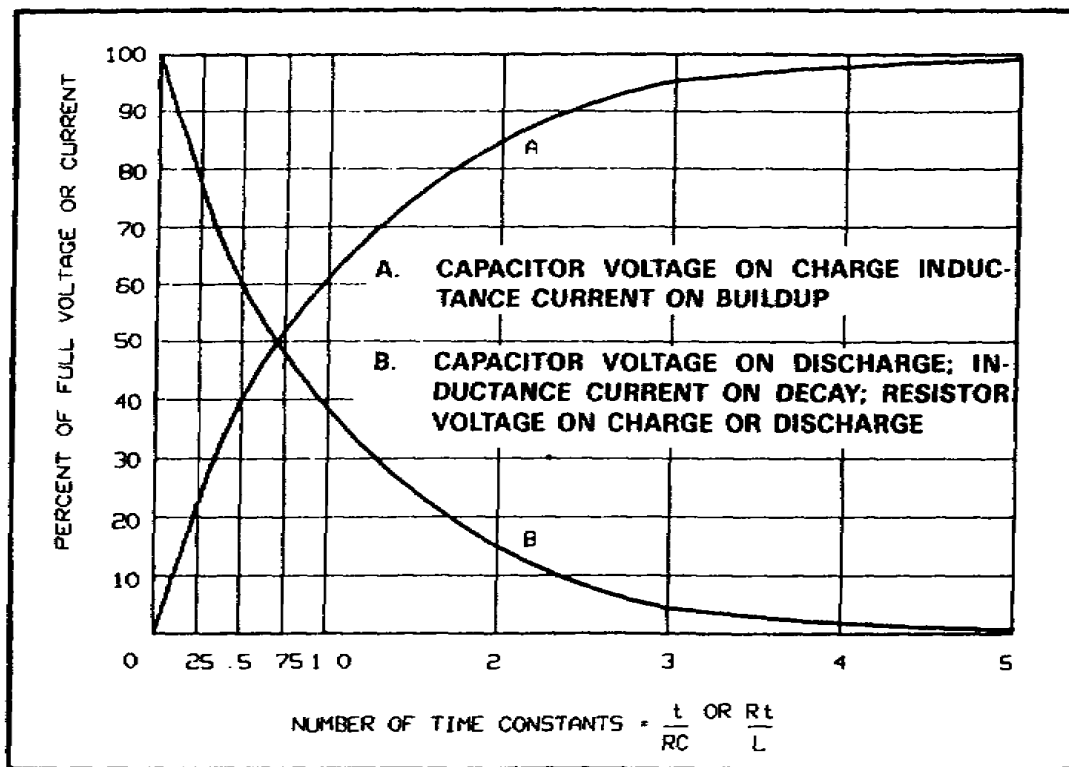


Figure 1-18. Universal Exponential Curves for RC and RL Circuits.

Square Wave Applied to RC Circuits. Square waves of voltage are often applied to series RC circuits in radar. The reason is either to use the RC circuit for coupling the undistorted square wave to a following stage, or to distort it purposely. In the latter case, the RC circuit is called a wave shaping circuit.

In AC circuit analysis, you learned that RC circuits do not affect the shape of the sine wave. If a sine wave of voltage is applied to the RC circuit, no matter what the values of resistance and capacitance are, its shape across either the resistor or the capacitor will be a sine wave. The only changes that would be evident would be in amplitude and phase. However, with a square wave applied to a series RC circuit, the values of resistance and capacitance have a direct effect upon the resultant wave shape across the resistor and the capacitor.

If the R and C of the circuit are such that the capacitor charges very rapidly and reaches full charge during the first part of the input wave, the output across the resistor will be a sharply peaked wave. The output across the capacitor will be a square wave with the leading edge rising with a slight curvature rather than rising vertically. On the other hand, if the capacitor and resistor are of such a value that the capacitor doesn't have time to charge, the output across the resistor may approximate the input, although the top of the wave will slope down. For values of resistors and capacitors between these two extremes, the wave shapes will differ.

You can think of a square wave of voltage as a DC voltage that alternates between a maximum and a minimum, each for the same length of time. One way of developing a square wave of voltage is by using the circuit shown in figure 1-19A. With the switch in position A, the output across the resistor is 50 V. With the switch in position B, the output is zero. If the switch is left in each position the same length of time and if the switching time is zero, the output is a square wave of voltage as shown in figure 1-19B.

The frequency of this square wave can be determined from the formula for frequency in terms of time,

$$f = \frac{1}{P}.$$

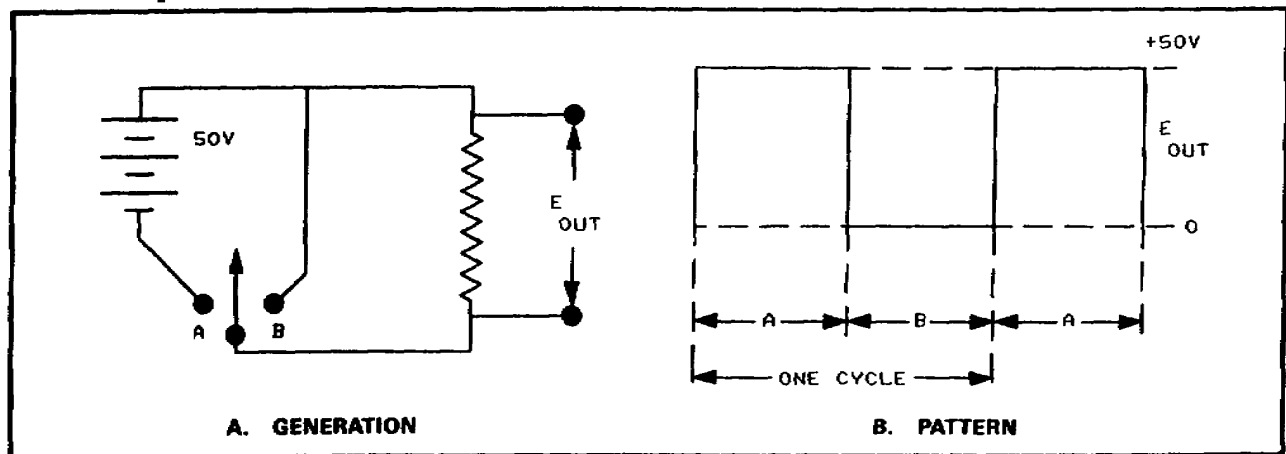


Figure 1-19. Square Wave.

In the preceding formula, if time is in seconds, the frequency will be in hertz; if the time is in microseconds, the frequency will be in megahertz. If the time is given in microseconds but it is desirable to have the frequency in hertz, then the formula can be written in this manner (instead of changing the microseconds to a fractional part of a second):

$$f_{\text{Hz}} = \frac{1,000,000 \mu\text{sec}}{P \mu\text{sec}}$$

P represents the time for one cycle. For example, find the frequency of a square wave if the switch in figure 1-19A is left in position A for 2,500 μsec and in position B for 2,500 μsec . The period for one cycle is the sum of two alternations or 5,000 μsec . Using the second formula,

$$f = \frac{1,000,000}{5,000} = 200 \text{ Hz.}$$

If the frequency is known but the period for one cycle is needed, rewrite the formula as follows:

$$P = \frac{1}{f}, \text{ where the time will be in seconds if the frequency is in hertz, and in microseconds if the frequency is in megahertz, or}$$

$$P = \frac{1,000,000}{f}, \text{ where the time will be in microseconds if the frequency is in hertz.}$$

If the frequency of a square wave is 250 Hz, what is the time for one cycle?

$$P = \frac{1,000,000 \mu\text{sec}}{250 \text{ Hz}} = 4,000 \mu\text{sec}$$

When the period for one cycle of a square wave is 4,000 μsec , the time for each alternation is 2,000 μsec . An alternation is the time the switch is in one position, either A or B in figure 1-19A.

To find out what happens when a square wave is applied to a series RC circuit look at figure 1-20. A square wave having a frequency of 250 Hz is applied to an RC circuit. Since the maximum voltage of the square wave is 50 V, the instant the square wave is applied to the RC circuit the applied voltage E_a will be 50 V. This 50 V input lasts for one alternation, 2,000 μsec .

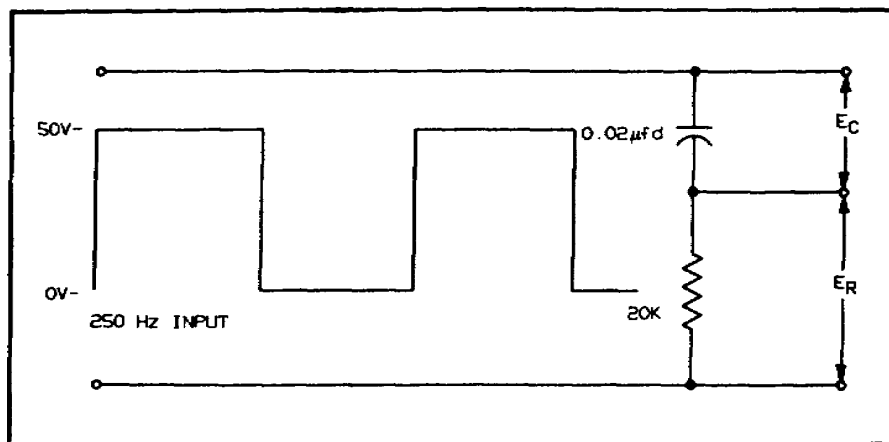


Figure 1-20. Sample RC Circuit.

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From the Universal Time Constant Chart, you can see that a capacitor cannot charge instantaneously. The voltage across the capacitor at time t_0 then is zero. Hence, all of the applied voltage appears across the resistor.

The values of E_R and E_C at time t_0 are shown on their respective wave shapes in figure 1-21. At the instant a DC voltage is applied to a series RC circuit, the voltage drop across the capacitor is zero, and all of the applied voltage appears across the resistor.

At time T_1 , just before the input drops to zero, the DC voltage has been applied for 2,000 μsec . This has given the capacitor time to charge exponentially to some voltage value. With a voltage other than zero across the capacitor, the voltage across the resistor will be less than the initial voltage. The value of E_R at time T_1 , is found to be

$$\text{time for one TC} = (0.02) (20K) = 400 \mu\text{sec}.$$

Voltage is applied for 2,000 μsec at T_1 ; therefore, there are 5 TCs at T_1 . Thus, the capacitor is fully charged (50V), the current has ceased to flow,

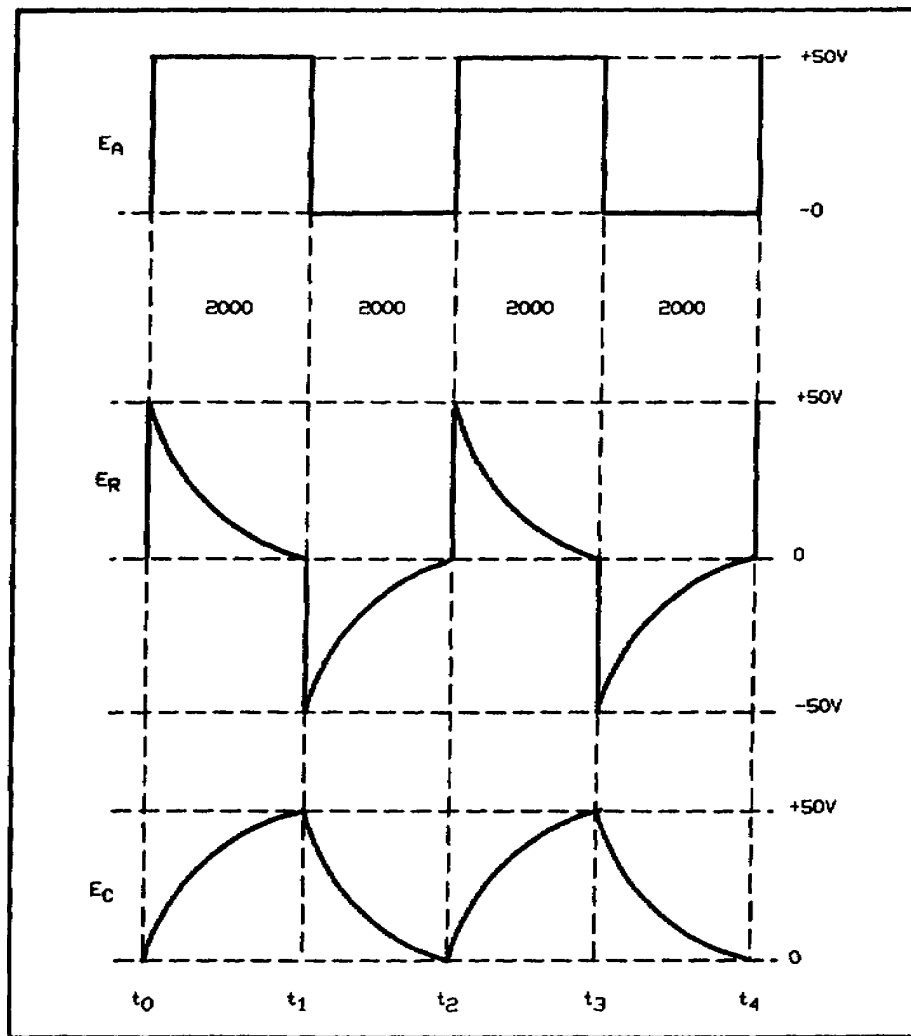


Figure 1-21. Wave Shapes for Circuit in Figure 1-20.

and the voltage across the resistor is zero. At T_1 , the input voltage drops to zero. The voltage across the capacitor is effectively the source voltage for the resistor.

Assuming that the input source has no internal resistance, the resistor is the only component in series with the capacitor. The capacitor begins to discharge through the resistor, reversing the direction of the original current flow (charging current). At time T_1 , after the input has dropped to zero, the resistor has approximately a negative 50 V across it (the voltage to which the capacitor is charged). Figure 1-22A shows the circuit at time T_1 , figure 1-22B is the simplified equivalent.

As the capacitor voltage decreases during the discharge, the resistor voltage also decreases. Since the resistor is the only component in series with the capacitor (figure 1-22B), E_C and E_R are always equal during this discharge of the capacitor. At time T_2 , just before the voltage rises from zero to maximum, the capacitor has been discharging for 2,000 μsec . The voltage across the capacitor and the resistor has been decreasing at an exponential rate during this time. The value of the voltage across them at time T_2 is shown in figure 1-21.

At time T_2 , the input voltage rises to maximum (50 V) again. A new cycle starts and the same action is repeated. The voltages at times T_2 , T_3 , and T_4 will be approximately the same as those at times T_0 , T_1 , and T_2 , respectively. The continuation of these wave shapes is shown in figure 1-21. These wave shapes are from the circuit of figure 1-20 under the conditions given; that is, with a capacitor of 0.02 fd, a 20,000-resistor, and an input having a frequency of 250 Hz. (fd is farads.)

If the relationship between T, R, and C is changed, the shape of the resistor and capacitor voltage curves will also change.

The RL (LR) Circuit. Wave shaping can be by RL circuits as well as by RC circuits. In RC circuits, you learned that the transitory time was the time needed for the capacitor to charge to the applied voltage and for the current to drop to zero. In a series RL circuit, on the other hand, the transitory time will be the time for current to build up to a maximum value from zero or to decay from maximum to zero.

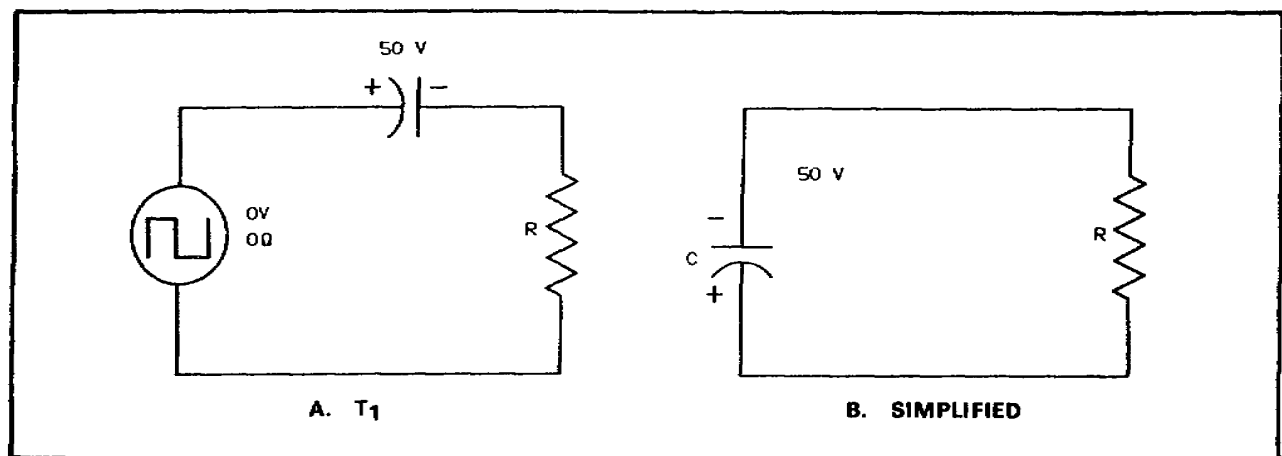


Figure 1-22. Circuit.

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Since the same laws hold true in RL circuits as in RC circuits, the same sort of analysis may be used. The sum of the instantaneous voltage drops around a series RL circuit is always zero. The product of the current and the resistance equals the voltage drop across the resistor.

In the RC circuits just studied, the capacitor opposed a sudden change of voltage across it. This caused the transient action. In RL circuits, the inductance (coil) opposes a sudden change of current flow through it giving a transient action. The rate at which current will change through a coil is dependent upon the voltage across the coil and the inductance of the coil. The current through the coil will increase faster with a large voltage across it than if the voltage were small. Also, the larger the inductance, the smaller the rate of change of current.

Figure 1-23A shows a series RL circuit with DC applied. At the instant the switch is closed, 50 VDC is applied to the inductor and the resistor in series. Because the inductor has the characteristic of opposing a change in current flow, there is no current flow through the resistor and no voltage drop across the resistor ($E_R = I \times R = 0 \times 10K$). All of the voltage must appear across the coil.

$$E_a = E_L + E_R$$

$$50 \text{ v} = E_L + 0 \text{ v}$$

With 50 V across the 10-henry (10-h) inductor, which is assumed to have no internal resistance, current begins to flow through the circuit at a rapidly changing rate.

After a short time interval, the current will have risen to 3 mamps. With 3 mamps of current, the voltage drop across the resistor is 30 V and across the coil it is 20 V (see figure 1-23B). With the lower voltage across the coil, the current change would be less rapid.

After another period of time, the current, since it is increasing more slowly than before, may rise to 4.2 mamps. This would place a voltage of 42 V across the resistor, leaving only 8 V across the coil (figure 1-23C).

Since the voltage across the coil has again decreased, the rate of increase of current is again smaller. After another period of time, the current might be 4.8 mamps. This would develop 48 V across the resistor, leaving 2 V across

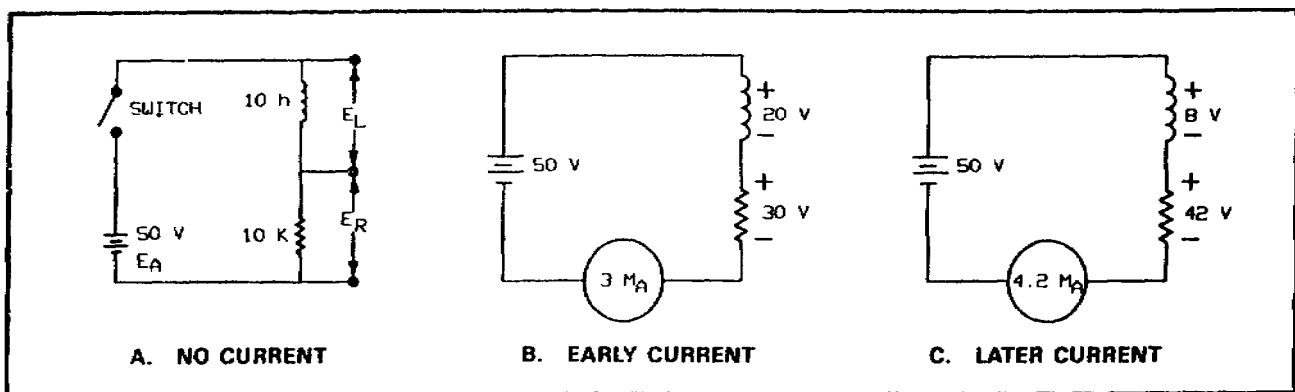


Figure 1-23. Voltages Across an RL Circuit.

the coil. Each time, if the voltage across the coil is halved, the current increase would be halved. Theoretically, the current would never reach maximum. For all practical purposes, however the voltage across the coil becomes zero, and the current reaches a steady state. This increase of current through an inductor is very similar to the increase of voltage across a charging capacitor

RL Time Constants. The rate of increase of current through a coil is directly proportional to the voltage across it and indirectly proportional to the inductance. The larger the inductance, the smaller the rate of increase. Therefore, since it must take longer for the current to reach maximum through a larger inductance, the time for the current to reach maximum is proportional to the inductance in the circuit.

The maximum current is equal to the applied voltage divided by the resistance in the circuit. The greater the resistance, the smaller the maximum current. Since it takes less time for the increasing current to reach a low value than it does to reach a high value, the time required must be inversely proportional to the resistance in the circuit.

It may be shown that something else in the RL circuit could affect the time required for the current through the coil to reach maximum. If the applied voltage is increased, the maximum current will be higher. This would appear to increase the time required but, at the same time, the rate of increase would be greater, tending to shorten the time. Thus, an increase in voltage would not affect the time required for the current to reach maximum value. It remains that the only factors affecting the time required for the current to reach maximum are the resistance and the inductance in the circuit.

In RC circuits, it was shown that both resistance and capacitance were directly proportional to the time required for completion of the transient action. In a series RL circuit, on the other hand, inductance is directly proportional to the transitory time, and resistance is inversely proportional. This relationship is shown in the following equation:

$$\text{Time} = L \times \frac{1}{R} = \frac{L}{R}.$$

This value L/R represents a period of time proportional to the transitory time in the RL circuit and is like the product of R and C in the RC circuit. Therefore, it is also termed a time constant. The relationship holds true when expressed in the following units:

$$\text{TC (in sec)} = \frac{\text{Inductance (in h)}}{\text{Resistance (in } \Omega)}$$

For example:

$$\text{TC} = \frac{10 \text{ mh}}{10 \text{ k}\Omega} = 1 \mu\text{sec}$$

At the end of the first TC in a series RL circuit, the current will have reached 63.2 percent of its maximum value. At the end of the second TC, the current will have increased to 86.5 percent of its maximum value; at the end of the third TC, 95.1 percent; at the end of the fourth TC, 98.2 percent; and at the end of the fifth TC, 99.3 percent of its maximum value.

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The current in a series RL circuit follows exactly the same curve in its buildup as the capacitor voltage followed in the RC circuit. For that reason, the Universal Time Constant Chart (figure 1-18) can be used for RL circuits as well as for RC circuits. Curve A on the graph represents current on buildup; curve B represents current on decay.

Square Wave Applied to RL Circuits. When a square wave of voltage is applied to a series RL circuit, results similar to those from RC circuits can be expected. For example, consider the circuit of figure 1-24A with a square wave of voltage applied. At the instant the input signal rises from zero to 20 V, the entire voltage appears across the inductor. There is no current flowing in the circuit as yet, since the inductance opposes any change in current. The voltage across the resistor, then, is zero. This is shown in the wave shapes of figure 1-24B.

As the current builds up in the circuit, the voltage across the resistor increases and that across the inductor decreases. At the end of the first alternation, the number of TCs is the duration of the alternation divided by the time of 1 TC, provided the wave is symmetrical.

$$\text{Number of TCs} = \frac{P_w}{TC} = \frac{P_w}{L/R} = \frac{Rt}{L}$$

In the circuit illustrated in figure 1-24,

$$P_w = 1/2f = \frac{1}{2(500 \text{ Hz})} = .001 \text{ sec and}$$

$$\frac{Rt}{L} = \frac{500 (.001 \text{ sec})}{.1 \text{ h}} = 5.$$

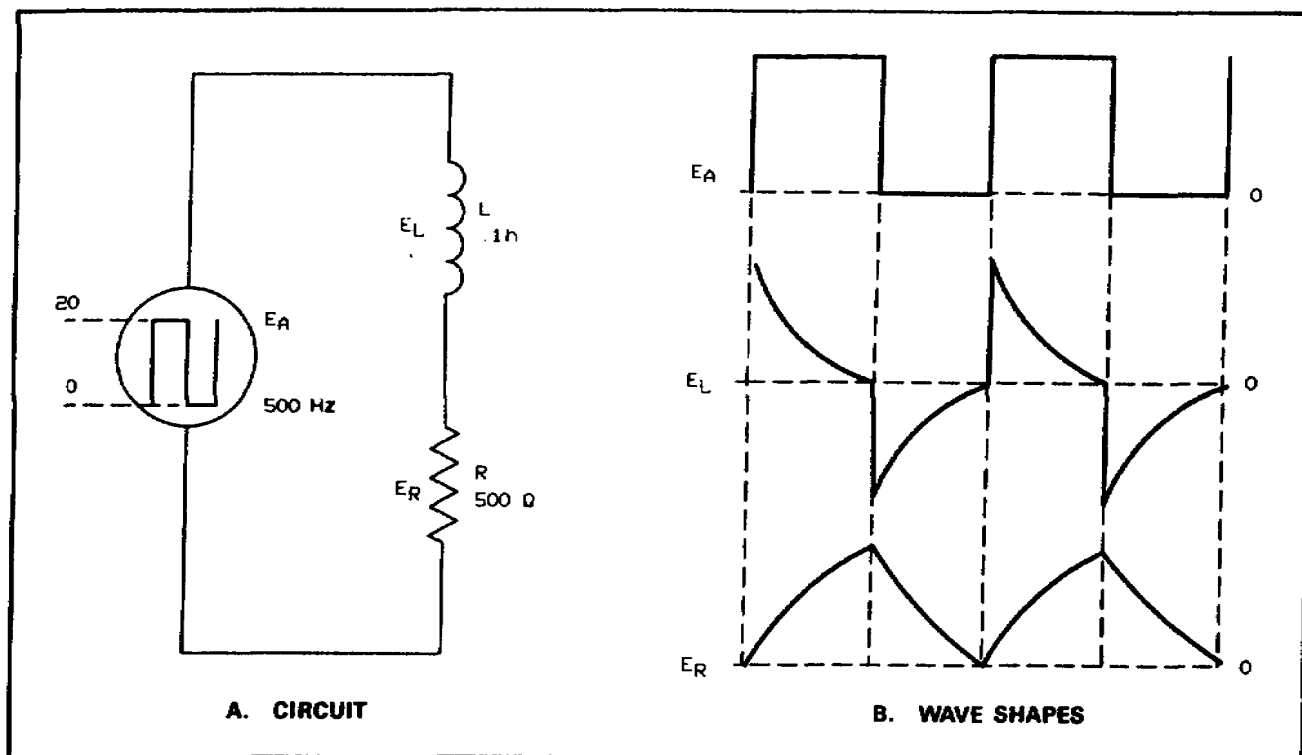


Figure 1-24. Square-Wave Voltage in an RL Circuit.

Therefore, the voltage across the coil at the end of the first alternation will be practically zero. These values are shown on the curves in figure 1-24B. The voltage across the coil is so near zero, you can assume that the current has reached maximum and is no longer increasing, therefore, the voltage across the resistor is maximum.

At the end of the first alternation, the input signal voltage drops to zero very suddenly. If you assume that the signal source has no internal resistance, then the circuit at this time may be represented by the circuit in figure 1-25.

With no applied voltage to sustain the current, which is at maximum, the current would attempt to stop flowing. The magnetic field, due to this current, would begin to collapse. The collapsing of the magnetic field induces a voltage across the coil of such a polarity that it tends to maintain the current flow in the same direction. The coil is now acting as a generator with the polarity shown in figure 1-25.

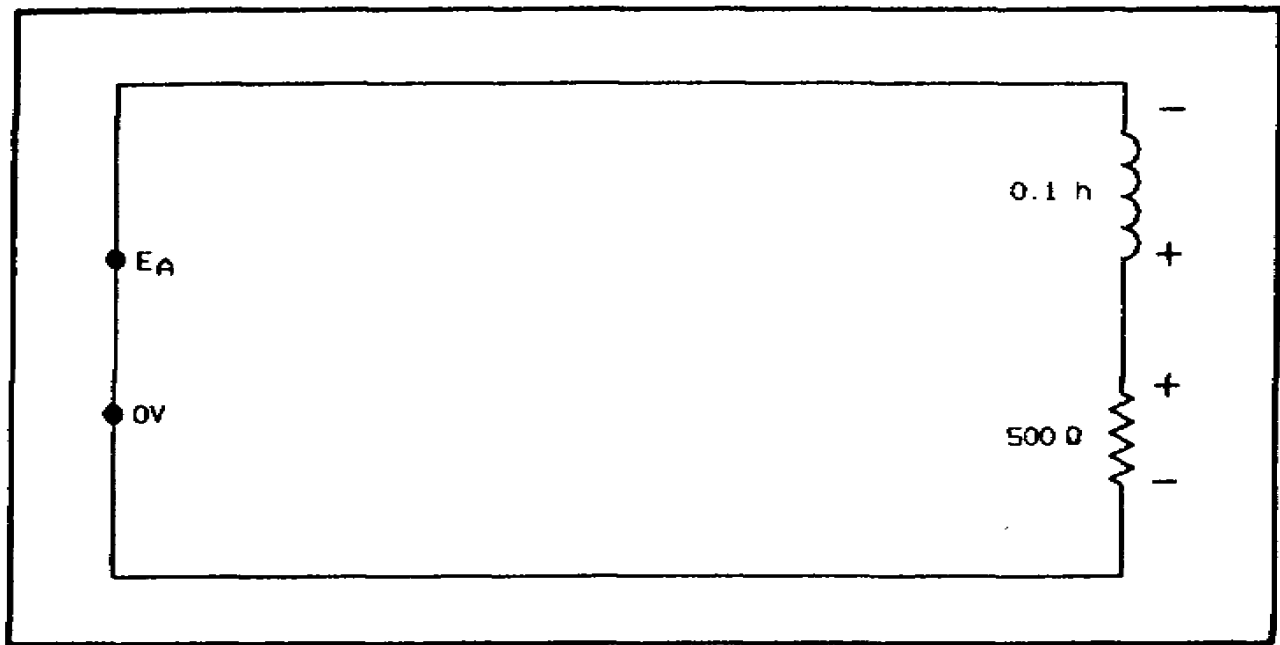


Figure 1-25. RL Circuit at End of First Alternation.

The instant the field begins to collapse, the greatest current will flow through the circuit, producing a high voltage drop across R. With no losses in the circuit, the voltage across both the resistor and the coil would have an amplitude of about 20 V. As the induced voltage falls off, the current decreases, as does the voltage, across the resistor. At any time during current decay, the voltage across the coil and the resistor will be equal in amplitude since the two are effectively in parallel.

Notice that the wave shape across the coil is AC, although the input voltage is pulsating DC (figure 1-24B). It is a peaked wave, as was the voltage across the resistor in the RC circuits previously studied. The voltage across the resistor in the RL circuits is a triangular wave. This compares to the capacitor voltage in the RC circuits.

Time constants affect the wave shapes in RL circuits, just as they do in RC circuits. If the current has more than enough time to reach maximum (the time constant is short compared to the time for the shortest alternation), the wave shape across the coil will be a sharply peaked wave. As with RC circuits, in order for the time constant to be short, the time of the shortest al

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ternation must be at last ten times as long as the time constant of the RL circuit. That is,

$$t = 10 \frac{L}{R} \text{ or } \frac{Rt}{L} = 10 \text{ (or more).}$$

In the preceding formula, R is the resistance in ohms; L is the inductance in henrys; and t is the time for the shortest alternation in seconds.

If the length of the TC for the circuit is very long, compared to the time for an alternation, the current does not have time to increase much. The voltage across the inductor produces a distorted square wave, while the voltage wave shape across the resistor is triangular.

In order for the output to be a good reproduction of the input the TC of the RL circuit must be long with respect to the time of the longest alternation. If the time of the alternation is only one-tenth (or less) of the time for one TC, the circuit is said to have a long TC. That is,

$$t = 0.1 \frac{L}{R} \text{ or } \frac{Rt}{L} = 0.1 \text{ (or less).}$$

Summation of RC and RL Circuits. RC and RL series and combinations are used primarily in radar circuits as wave shaping or timing devices. A time constant may be established for each RC and RL circuit. This TC represents a period equivalent to the time required for the circuit to complete approximately 63.2 percent of its transient action. That is, the capacitor in the RC circuit can charge to 63.2 percent of the applied voltage in 1 TC and the current in the RL circuit can increase to 63.2 percent of the maximum current for the circuit in 1 TC. These transitory periods last for about 5 TCs.

In any series RC circuit, 1 TC is the product of the resistance and the capacitance. In any series RL circuit, 1 TC is the quotient of the inductance and the resistance L/R.

The number of time constants in a specified time can be determined by dividing the specified time by the value of one time constant. In RC circuits,

$$\text{number of TCs} = \frac{t}{RC}.$$

In RL circuits,

$$\text{number of TCs} = \frac{Rt}{L}.$$

Summary. The charging of the capacitor in a series RC circuit and the current rise in a series RL circuit follow exponential curves. The Universal Time Constant Chart can be used for both RC and RL circuits in order to determine the percent of transient action completed in any specified number of TCs.

A circuit is said to have a long time constant when the time required for transient action is long compared to the time allowed to charge. A circuit has a short time constant when the transient time is short compared to the time allowed to charge. Thus by definition,

$$\frac{t}{RC} = 0.1 \text{ (or less), } \frac{t}{RC} = 10 \text{ (or more),}$$

$$\frac{Rt}{L} = 0.1 \text{ (or less), } \frac{Rt}{L} = 10 \text{ (or more).}$$

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What is a characteristic of a resonant circuit?
 - a. R equals X_C .
 - b. R equals X_L .
 - c. X_C is unequal to X_L .
 - d. X_C equals X_L .
2. How can the current be increased in this circuit? See figure 1-26.
 - a. By increasing the frequency.
 - b. By decreasing the frequency.
 - c. By decreasing R .
 - d. By decreasing X_L .

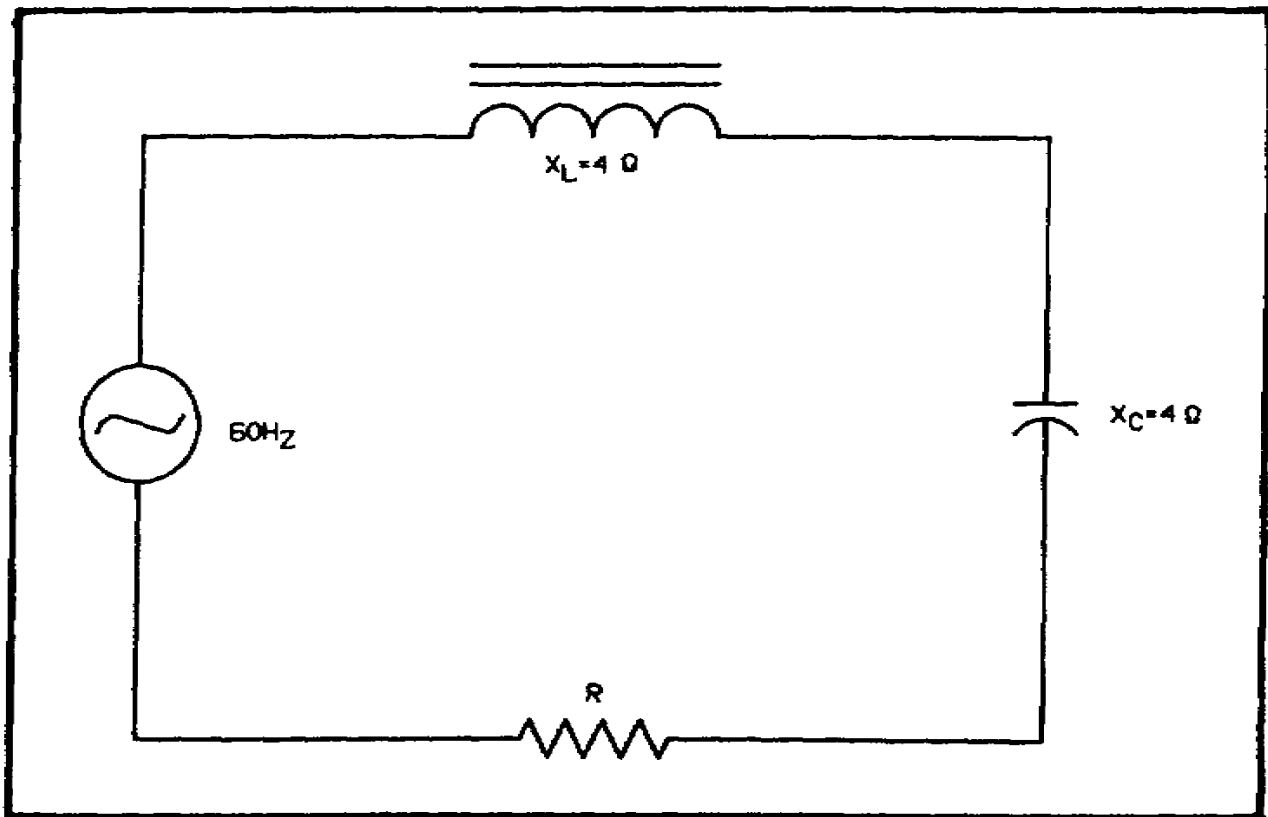


Figure 1-26. RLC (Resonant) Circuit

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3. Which points, at resonance, in this circuit are used to measure the largest voltage drop? See figure 1-27.
- AD.
 - AC.
 - BA.
 - BD.
4. How will an increase in frequency affect this circuit? See figure 1-27.
- Current increases.
 - Total impedance decreases.
 - Voltage across R decreases.
 - Voltage across R increases.

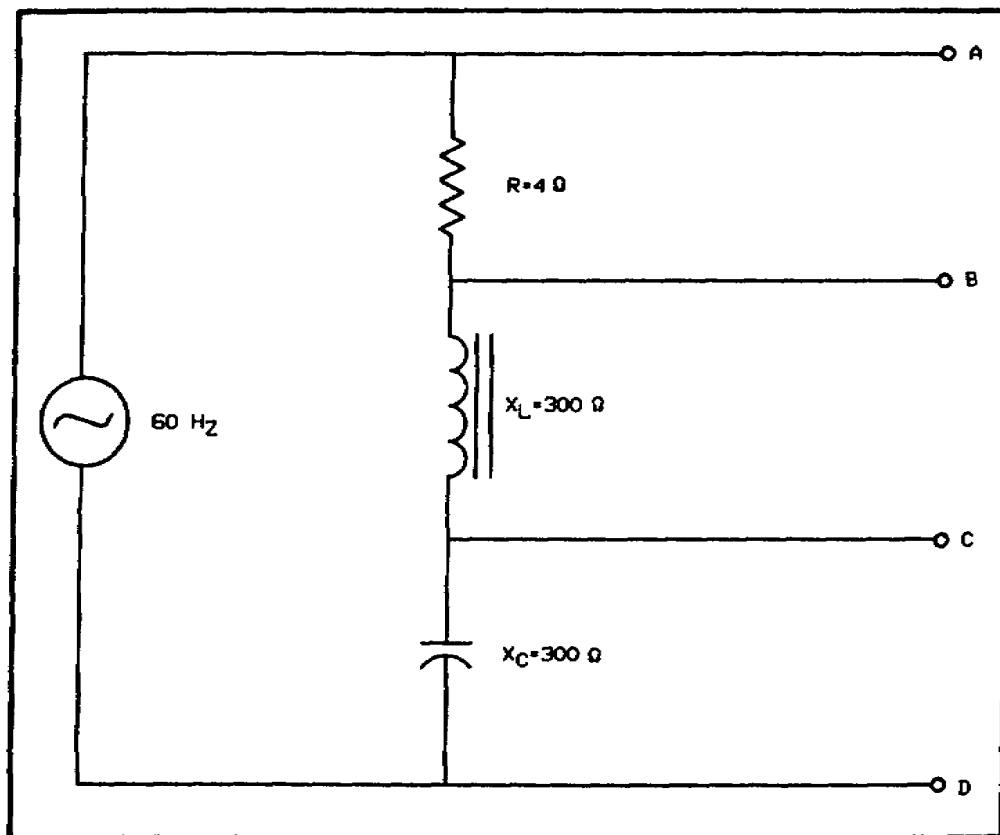


Figure 1-27. Voltage Drop Across an RC or LR Circuit.

5. What is the band pass, in hertz, from this current curve? See figure 1-28.
- 4,000.
 - 3,000.
 - 2,000.
 - 1,000.

6. What points are represented by A and B? See figure 1-28.

- a. Control.
- b. Half power.
- c. Full power
- d. Limiting.

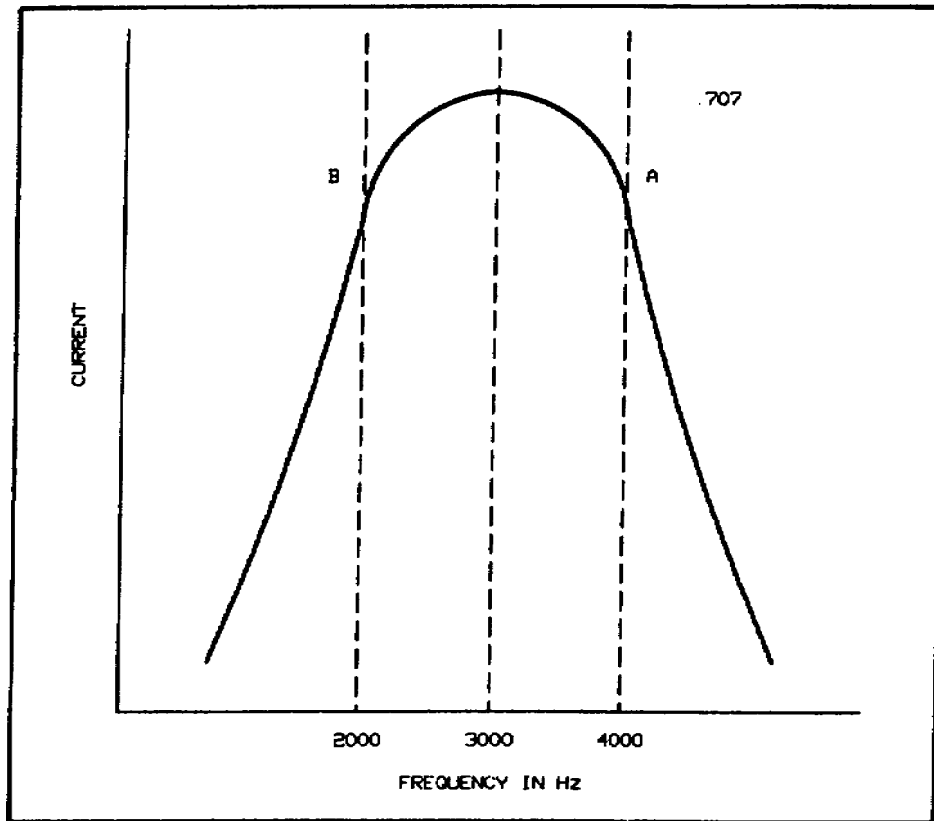


Figure 1-28. Frequency Band Pass.

7. Under what conditions will a series resonant circuit act inductively?

- a. At frequencies above resonance.
- b. At frequencies below resonance.
- c. At high-voltage amplitudes.
- d. At low-voltage amplitudes.

8. What size capacitor, in fd, will provide a 60-Hz resonant frequency from a 0.265-h inductor in a series circuit?

- a. 0.265.
- b. 2.65.
- c. 26.5.
- d. 265.

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9. What resonant circuit has maximum current and minimum reactance?
- Inductive.
 - Capacitive.
 - Series.
 - Parallel.
10. What is the Q of a series resonant circuit that contains $400\ \Omega$ of inductive reactance and $5\ \Omega$ of resistance?
- 160.
 - 80.
 - 40.
 - 20.
11. What is the characteristic of a parallel LC resonant circuit?
- Current is maximum.
 - Impedance is maximum.
 - Voltage drop is minimum.
 - Impedance is minimum.
12. What characteristic applies for both series and parallel resonant circuits having the same size components?
- Equation for resonant frequency.
 - Equation for resonant reactancies.
 - Current at resonance.
 - Voltage at resonance.
13. How can the time constant be increased? See figure 1-29.
- Decrease R.
 - Decrease C.
 - Increase E.
 - Increase R or C.
14. What is the current value, in milliamperes, $1,200\ \mu\text{sec}$ after switch S is closed if E_b equals 100 V? See figure 1-29.
- 62.6.
 - 16.8.
 - 1.81.
 - 0.8.

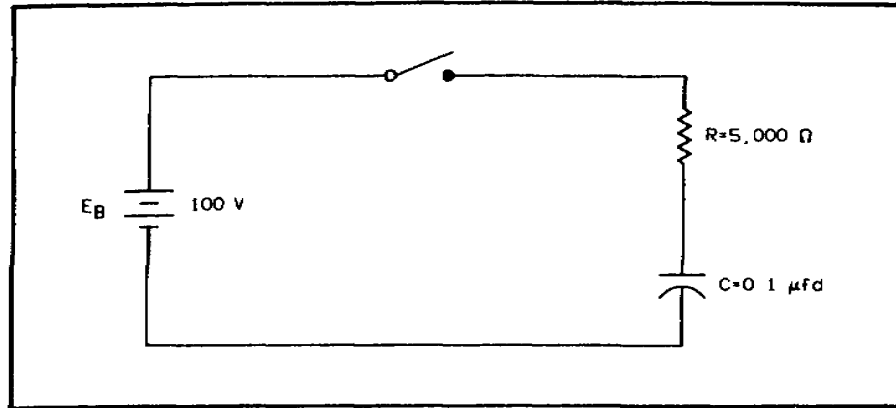


Figure 1-29. RC Circuit in Series.

15. What is the output voltage wave shape across the resistor? See figure 1-30.

- a.
- b.
- c.
- d.

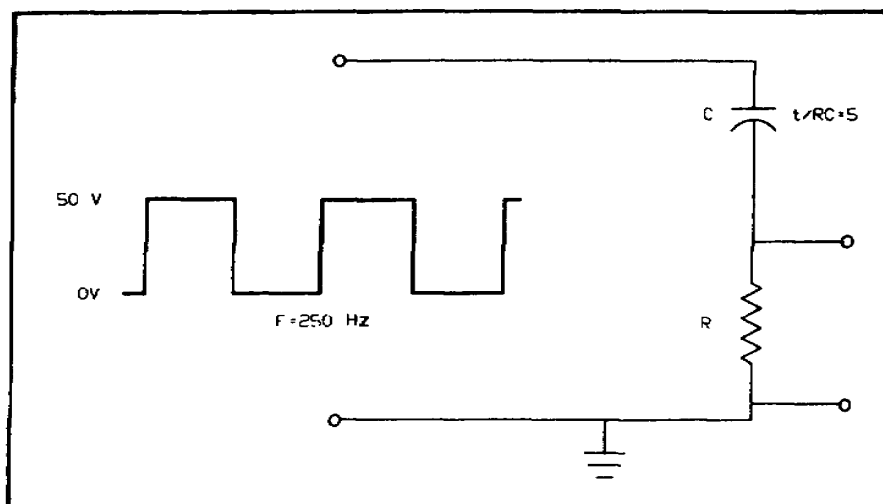


Figure 1-30. Wave-Shaping Circuit.

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16. Which ratio indicates a long time constant?
- a. $\frac{Rt}{L} = 10$ or more.
 - b. $\frac{Rt}{L} = 0.1$ or less.
 - c. $\frac{Rt}{L} = 1$.
 - d. $\frac{Rt}{L} = 5$.
17. What BEST describes the rate at which a capacitor changes its charge?
- a. Maximum during first TC.
 - b. Minimum during first TC.
 - c. Minimum during third TC.
 - d. Maximum during third TC.
18. How many TCs are required for the current to go from minimum to 99.3 percent of maximum in a series RL circuit?
- a. 3.
 - b. 4.
 - c. 5.
 - d. 10.
19. It is desired that the current through block 3 be very low at 20 kHz and very high at 30 kHz. What type of circuits should blocks 1 and 2 contain? See figure 1-31.
- a. One series resonant at 30; 2 series resonant at 20.
 - b. One series resonant at 20; 2 series resonant at 30.
 - c. One parallel resonant at 20; 2 parallel resonant at 30.
 - d. One parallel resonant at 20; 2 series resonant at 30.

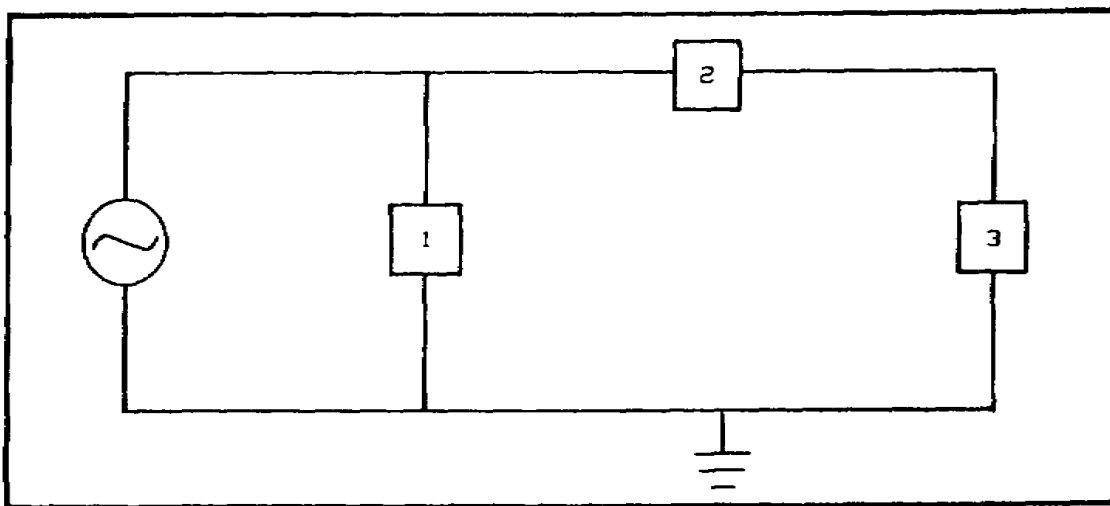


Figure 1-31. Resonant Loader.

20. What type of time constant is employed in this circuit? See figure 1-32.

- a. Short.
- b. Medium.
- c. Moderate.
- d. Long.

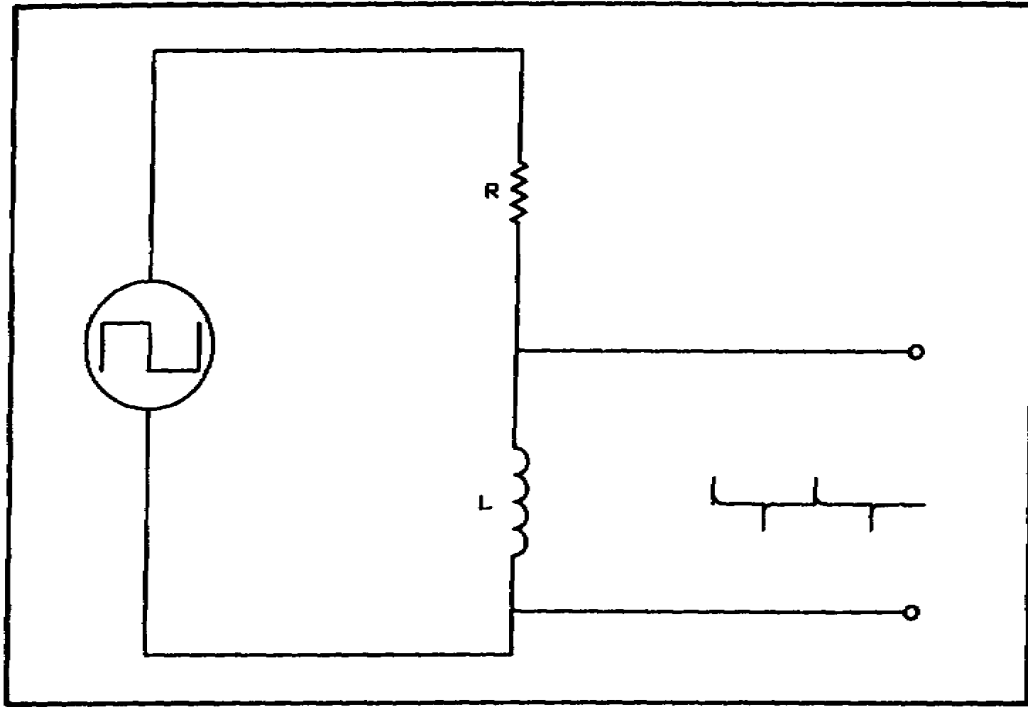


Figure 1-32. RL Circuit.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed four or more questions, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 2 FILTERS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to explain the purpose, operation, and use of electronic filters.

Conditions. You will have this subcourse book and work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 3, and 4 (answer 23 of the 30 questions correctly.)

CHARACTERISTICS

Description

A filter is a circuit containing a number of impedances consisting of resistors, inductors, or capacitors. These impedances are grouped together to produce a definite frequency characteristic. Filters separate AC from DC, low-frequency current from high-frequency current, or signals within a band of frequencies from signals outside this band. Although resistors provide a uniform attenuation factor to all frequencies and although the impedance of an inductor or capacitor varies according to the frequency of operation, resistor-capacitor (RC) filters are quite often used. Filters permit free passage over a certain range of frequencies and reject or transmit poorly over another range of frequencies. The range where transmission occurs freely is called the pass band, and the range of poor transmission is called the attenuation or stop band. The frequency at which attenuation starts to increase rapidly is known as the cut-off frequency.

Configurations

There are three basic configurations into which filter elements can be assembled: The L (half section), consisting of one series and one parallel (shunt) arm. The full T-section, consisting of two series arms and one shunt arm. The full or π section, consisting of one series arm and two shunt arms.

Several sections of the same configuration can be joined to improve the attenuation or transmission characteristic. When filters are inserted in a circuit, they are usually terminated by resistances of the same value at both the input (generator) and output (load) for impedance matching. The value of the terminating resistance is usually determined by the circuit with which the filter is used. The desired cutoff frequencies are also predetermined. You have to know the values of capacitors and inductors, which give the desired frequency characteristics, when designing a filter.

Purpose

Filters are sometimes used in home cooling or heating systems to remove dirt or moisture from the air. Similarly, in electronics, filters are used to remove unwanted, undesirable frequencies from a circuit before the output is distributed to other parts of a system. Two examples are the removal of the ripple frequency from a power supply and all but the desired frequency at a receiving antenna. Whether low pass, high pass, or a combination of both, each circuit is designed to obtain something: hum-free operation, better tone quality, or separation of the many signals received by a radio antenna.

Operation

The operation of filter circuits may best be understood by the use of two formulas: inductive reactance

$$X_L = 2\pi fL,$$

and capacitive reactance

$$X_C = \frac{1}{2\pi fC}.$$

These formulas are explained in detail in the previous subcourse, MM0703, Basic Electricity, Part I.

Inductive Reactance. Inductive reactance is the product of the constant 2π and the variables frequency and inductance. A change in reactance is, therefore, directly proportional to a change in either of the variables. When frequency decreases, inductive reactance, or opposition offered by the inductor, also decreases. An increase in frequency, however, encounters more opposition from the inductor, so an inductor offers less reactance to low frequencies than to high frequencies. (For this discussion of filters, only frequency changes and the resulting change in opposition are considered.)

Capacitive Reactance. The formula for capacitive reactance shows that frequency and capacitance are the reciprocal of the reactance and that there is an inversely proportional relationship between them. When frequency increases, the reactance decreases, and the opposition of the capacitor to higher frequencies becomes smaller. Just as an inductor offers less opposition to low frequencies, a capacitor offers less opposition to high frequencies. Consequently, the choice of a capacitor or an inductor in filtering will be determined, to a large extent, by the frequency range you want to pass or reject.

FILTER DESIGN

Process

The design of filter circuits is a complicated mathematical process, with many advantages and disadvantages. Although a filter will pass or reject the desired frequency or band of frequencies, filtering of an input signal is not the only result that may be needed. The attenuation of the signal by the filter circuit and limited circuit flow in the load circuit, must also be considered. Formulas that provide the desired result in one particular case must often be revised to achieve the correct result in another.

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Power Supplies

Receiver. The design of a filter for the use in a receiver power supply is a relatively simple matter. Current requirements and output voltages are comparatively low, and high-inductance chokes (choke is the term used in filters for inductors) and high-capacity filter capacitors cost little. The usual procedure is to select a cutoff frequency well below the fundamental ripple frequency, and with a given capacitor, calculate the required inductance. In most cases, L and C are much larger than is actually required for satisfactory filtering. Such a filter is called a “brute force” filter.

Transmitter. The design problem is quite different in filters for transmitter power supplies. With high current drain, the choke must be wound with large wire and the core must contain plenty of iron to avoid saturation. The high voltages also demand additional insulation precautions. The filter capacitors must be rated at a much higher breakdown voltage. Where a 30-h choke for a receiver supply may be quite expensive, the cost of a 30-h choke for a 20,000-V, 6-amp supply would be practically prohibitive and enormous in size. Where an 8- μ fd electrolytic capacitor costs only a few cents, a 1- μ fd filter capacitor, to be used in a 20,000-V power supply, may cost several thousands of dollars. Thus, in the design of filters for transmitter power supplies, cost is a major factor.

The filter is designed to provide just enough attenuation of the ripple frequency to satisfy the requirements of the transmitter.

RESISTOR-CAPACITOR FILTER CIRCUITS

When it is necessary to separate the DC and AC that may be flowing in a circuit, a capacitor may be used to provide a path for the AC and a resistor to provide a path for the DC. Diverting the signal current through the capacitor will not affect the voltage drop across the resistor.

Low-Pass Filters

Low-pass filters are commonly used after the rectifier networks in power supplies. In order to convert the pulsating DC output of the power supply to a low ripple current, the low-frequency ripple must be reduced. Low pass filters are also used to reject the higher of two frequencies and pass the lower.

L-section. This low-pass filter, in its simplest form, is an inductance in series with the line and a capacitor across the line (figure 2-1). Also called a half-section filter, the L-section offers high resistance at high frequencies to the flow of current toward the load, because the inductive reactance of the coil is large. Also, most of the high-frequency current that gets through the coil passes through the capacitor, whose reactance to high frequencies is low; the high frequency does not reach the outputs. For low-frequency or DC currents, the inductive reactance is small and the capacitive reactance is large. Accordingly, these currents readily pass through the coil to the load.

Another analysis of a low-pass filter is done by comparing the voltages developed in the output at the low and high frequencies. Remember, “low-pass filter” means that a high voltage output is developed at the low frequency to

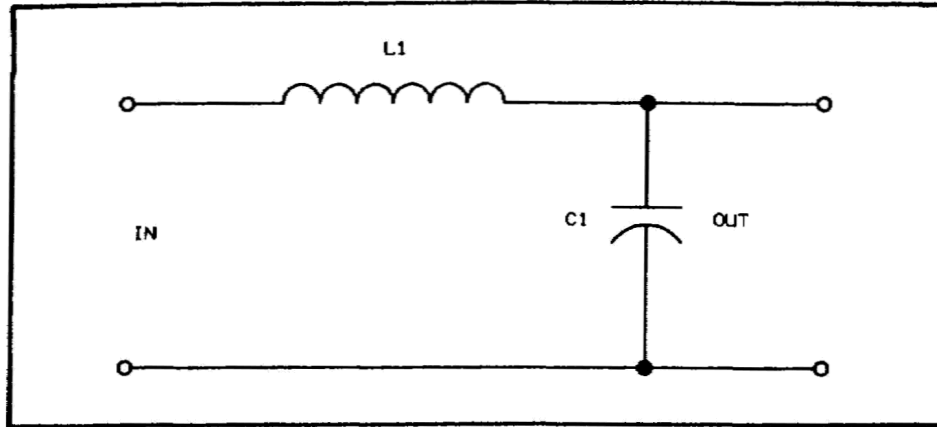


Figure 2-1. L-Section, Low-Pass Filter.

perform the required function such as supplying a picture to a TV screen, causing music in a radio, or positioning an antenna or missile.

In the low-pass filter shown in figure 2-1, note that the output voltage is developed across the capacitor. Recall the formula

$$X_C = \frac{1}{2\pi fc}$$

Note that X_C is large for low frequencies and small for high frequencies. Voltage is directly proportional to impedance, and there will be a large voltage developed on the capacitor at low frequencies and a small voltage developed at high frequencies.

This filter can be designed to develop almost all of the input voltage at low frequencies. The filter is then passing the low frequencies because the output voltage at low frequencies is large enough to perform the desired function. Very little voltage at low frequencies will be lost on the coil because it has very little opposition to low frequencies.

T-section. The operation of the T-section (figure 2-2) is similar to that of the L-section. However, the addition of L2 in the circuit, with its corre-

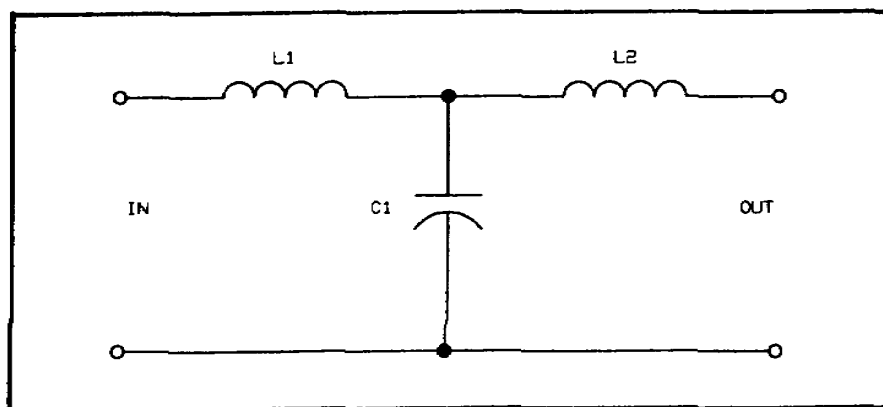


Figure 2-2. T-Section, Low-Pass Filter

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spondingly large inductive reactance to high frequencies, offers high resistance to the high frequency current that gets by L_1 and C_1 . Consequently, the T-section is much more effective, at any given frequency, than the L-section. The total of the two inductors' inductive reactance is equal to the single inductor used in the L-section. (This assumes that both circuits are to pass the same frequencies.)

π section. In the T-section and L-section filters, the input component is an inductor, and the circuit is called an inductive input filter. In all three, there are two principal characteristics: the inductance is in series with the line, and the capacitance is across the line. The π -section uses a capacitive input (figure 2-3). Although it is important that the outputs from the inductive and capacitive input filters differ in that the voltage output is higher with a capacitive input, frequency variations are the main consideration in this lesson. The capacitor C_1 shorts most high frequency currents to ground, while C_2 provides a path to ground for those currents that manage to get through L_1 . Thus, the total capacitive reactance should be equivalent to the single capacitance of the L-section and T-section filters.

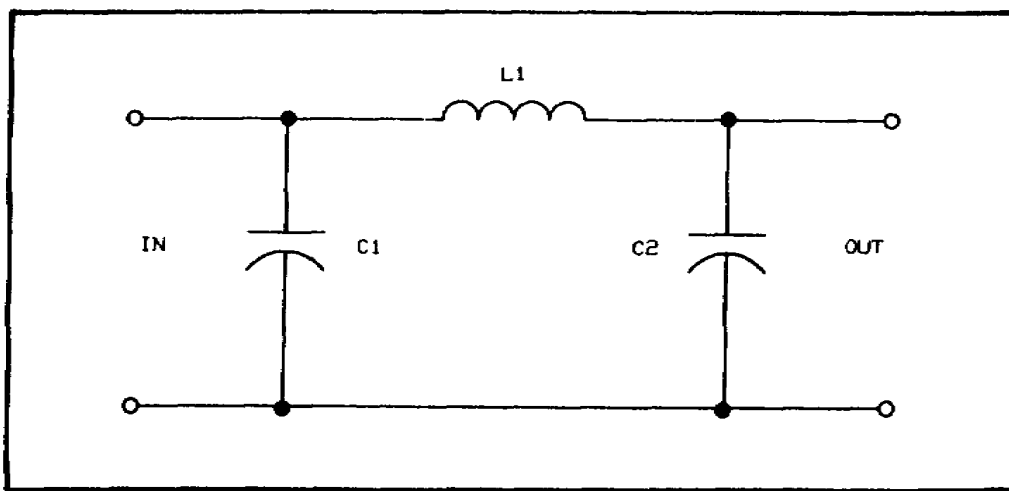


Figure 2-3. π -Section, Low-Pass Filter.

Transmission Characteristics. The output responses illustrated in this lesson are representative of specific filter circuits, but do not think of them as the only outputs from the filters discussed. This is particularly evident in figure 2-4B where it is indicated that additional sections, as well as different values of components, will very definitely alter the output response. Also affected by circuit changes would be the cutoff frequency, the bandwidth, and the attenuation factor of the filter network.

High-Pass Filters

High-pass filters are used to pass high frequencies and reject low frequencies. A common use is to couple AC signals while rejecting the DC voltage in amplifier sections.

L-section. The action of the L-section, high-pass filter (figure 2-5) is as follows: at low frequencies, the capacitance in series offers large opposition to the flow of current. Any low-frequency current from the input that gets

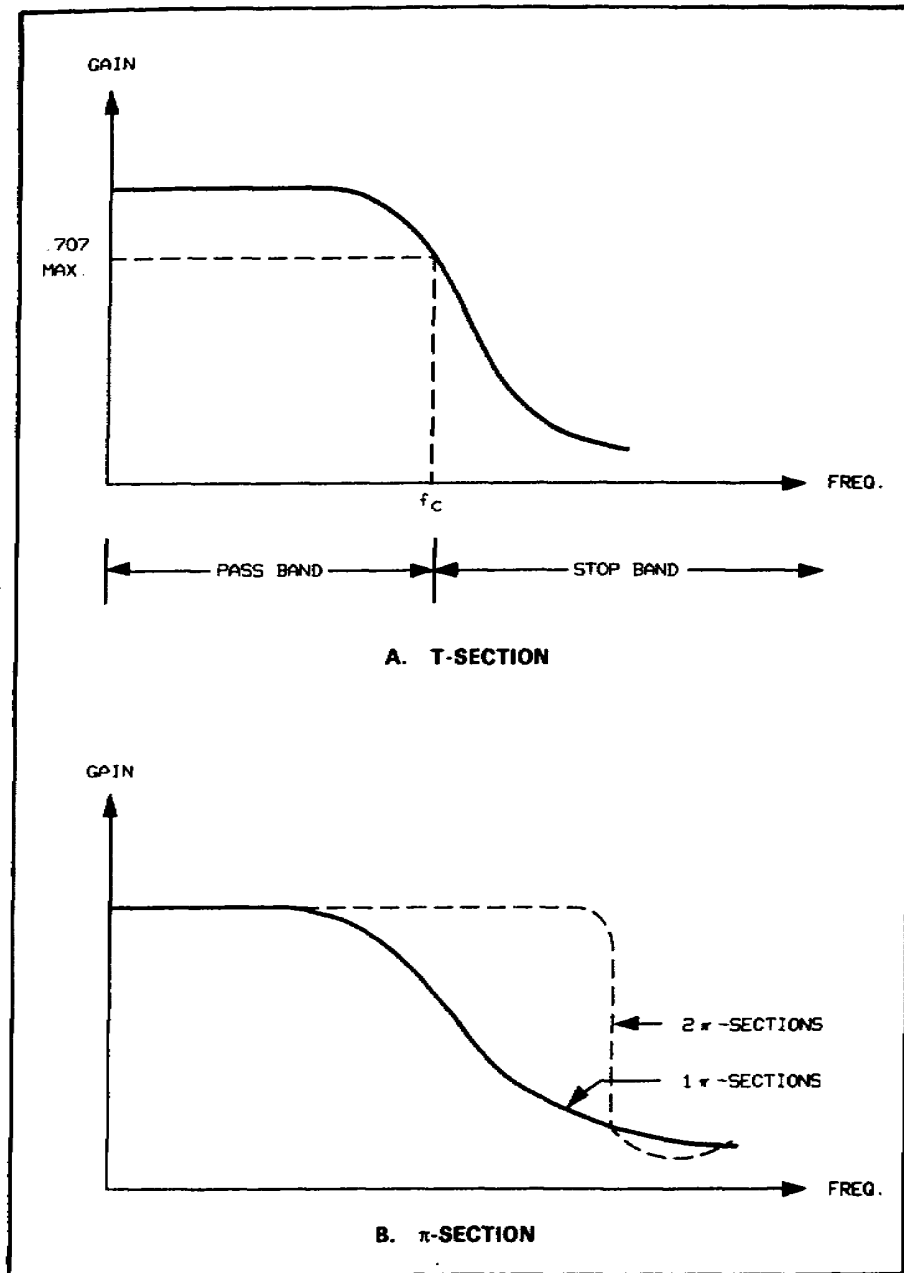


Figure 2-4. Comparison of Filter Quality.

through the capacitor passes through the coil, whose reactance at low frequencies is small. The result is that it does not reach the output. For high-frequency currents, the capacitive reactance is small, and the inductive reactance is large. Consequently, these currents pass readily through the capacitor to the output and very little current is diverted through the coil.

The output voltage of the high-pass filter in figure 2-5, is developed across the coil. This high-pass filter develops enough voltage across the coil at high frequencies to perform required functions.

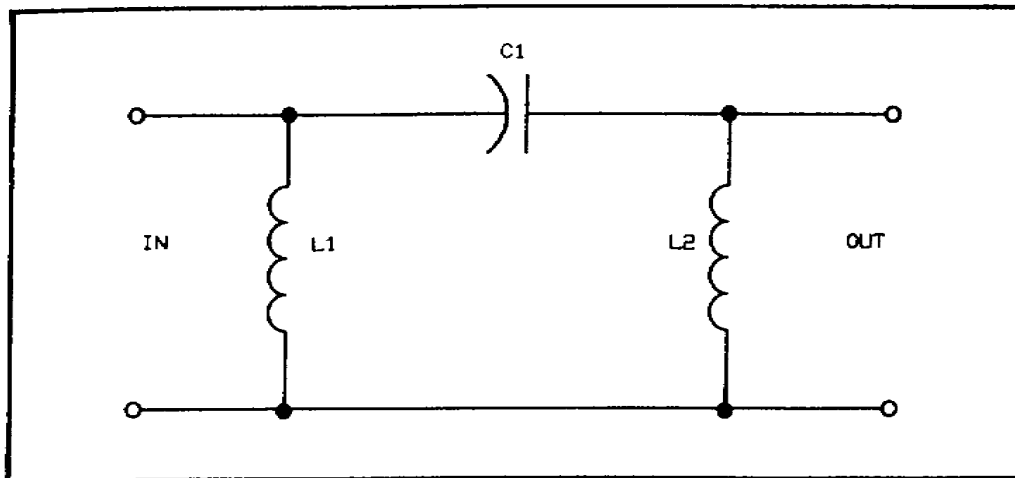


Figure 2-5. L-Section, High-Pass Filter

From the formula for inductive reactance, $X_L = 2 \pi fL$, you can see that for high frequencies X_L is large, and for low frequencies, small. Since voltages are directly proportional to impedances, it follows that much voltage is developed for the output at high frequencies, and very little at low frequencies. That means this filter will pass high frequencies.

T-section. The T-section (figure 2-6) uses the principles that capacitors in series act like resistances in parallel. The total capacitance of C_1 and C_2 should be equal to C_1 of the half section, to provide a low opposition path to the output for high frequencies. C_2 further insures that any AC variations across L_1 will be delivered to the load.

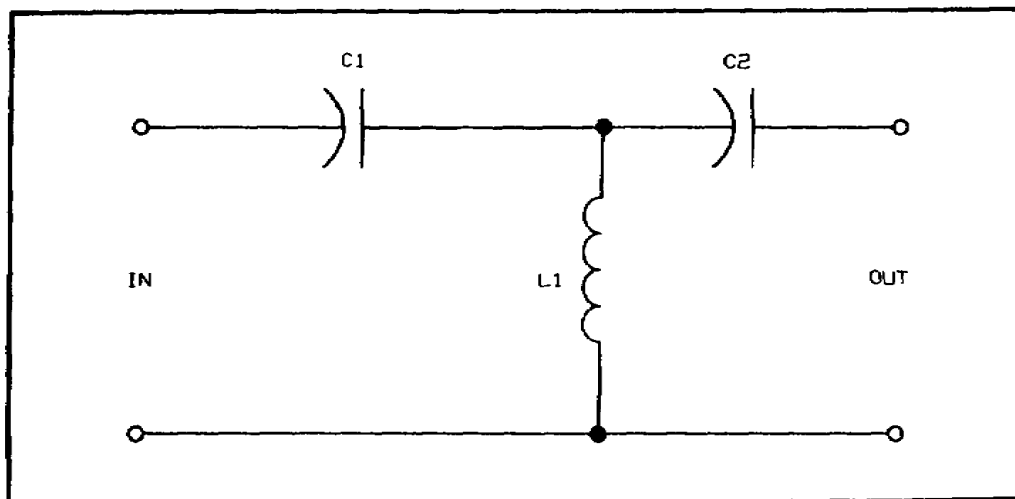


Figure 2-6. T-Section, High-Pass Filter.

π -section. The inductors L_1 and L_2 act much the same as the two capacitors in the π -section low-pass filter (figure 2-7); however, the low-frequency currents are provided two paths to ground in order to eliminate all but the higher-frequency currents. Capacitor C_1 presents a high impedance path to the output for low frequencies as well as a low-impedance path for the desired frequency.

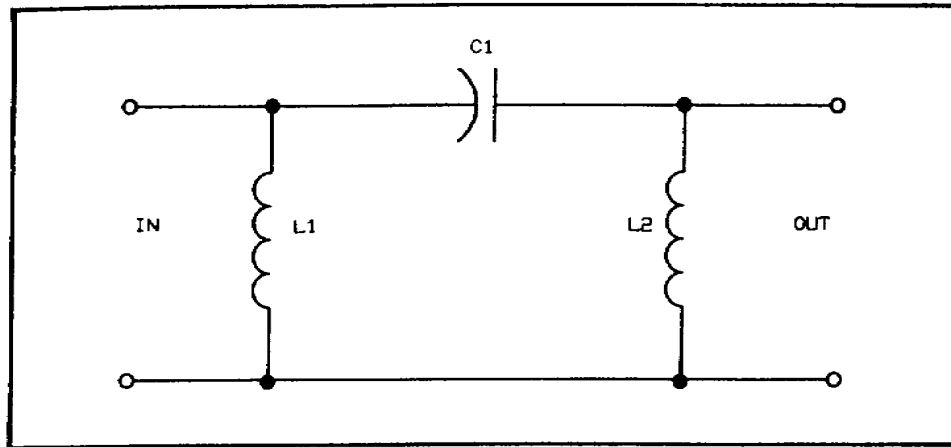


Figure 2-7. π -Section, High-Pass Filter.

Transmission Characteristics. By comparing figures 2-4 and 2-8, you can see that the arrangement of the components in a circuit can completely change its operation. Assume, for example, that the cutoff frequency of the lowpass filters in figure 2-4 is 10 kHz, interchanging the inductor and capacitor would reverse the stop and pass bands but leave the cutoff frequency at 10 kHz, as in figure 2-8.

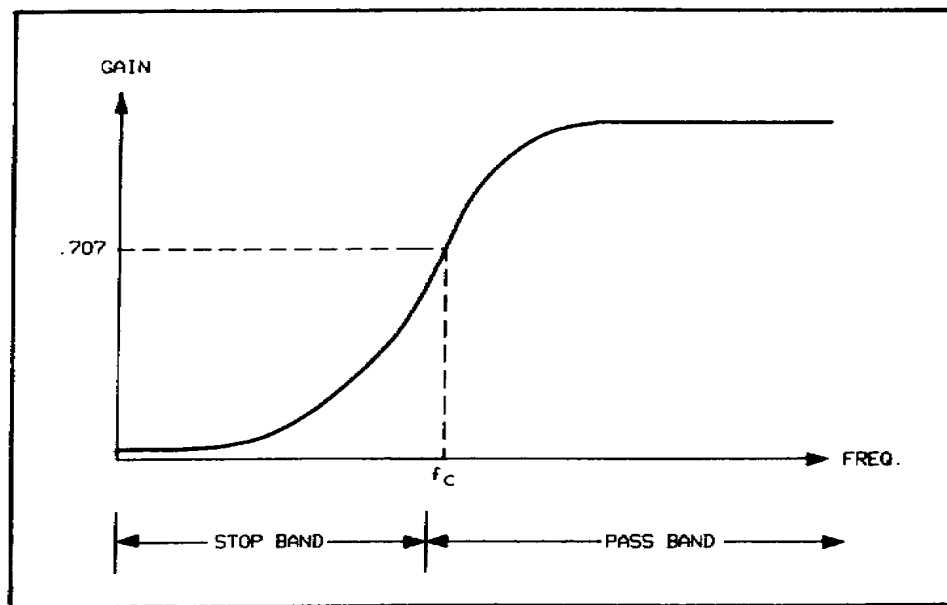


Figure 2-8. Transmission Characteristics of High-Pass Filters.

Band-Pass Filters

Band-pass filters are used where noise over a wide range requires filtering. It restricts all but a small band of frequencies.

L-section. The use of resonant circuits in filter networks provides a more selective method for filtering. A circuit consisting of a coil and a capacitor in parallel has an extremely high impedance at its resonant frequency, and

there is maximum tank (series resonant) current. Very little line current will flow at this frequency (figure 2-9A). By contrast, an inductor and a capacitor in series allows maximum current at their resonant frequency (figure 2-9B). Therefore, careful selection of series and parallel resonant circuits can determine at which frequency current flows to the load. In the tank circuit (figure 2-9C), L_1 and C_1 transmit freely between f_1 and f_2 , while the parallel tank affords an easy path for frequencies below f_1 (through L_2) to ground, as well as a path for frequencies above f_2 (through C_2).

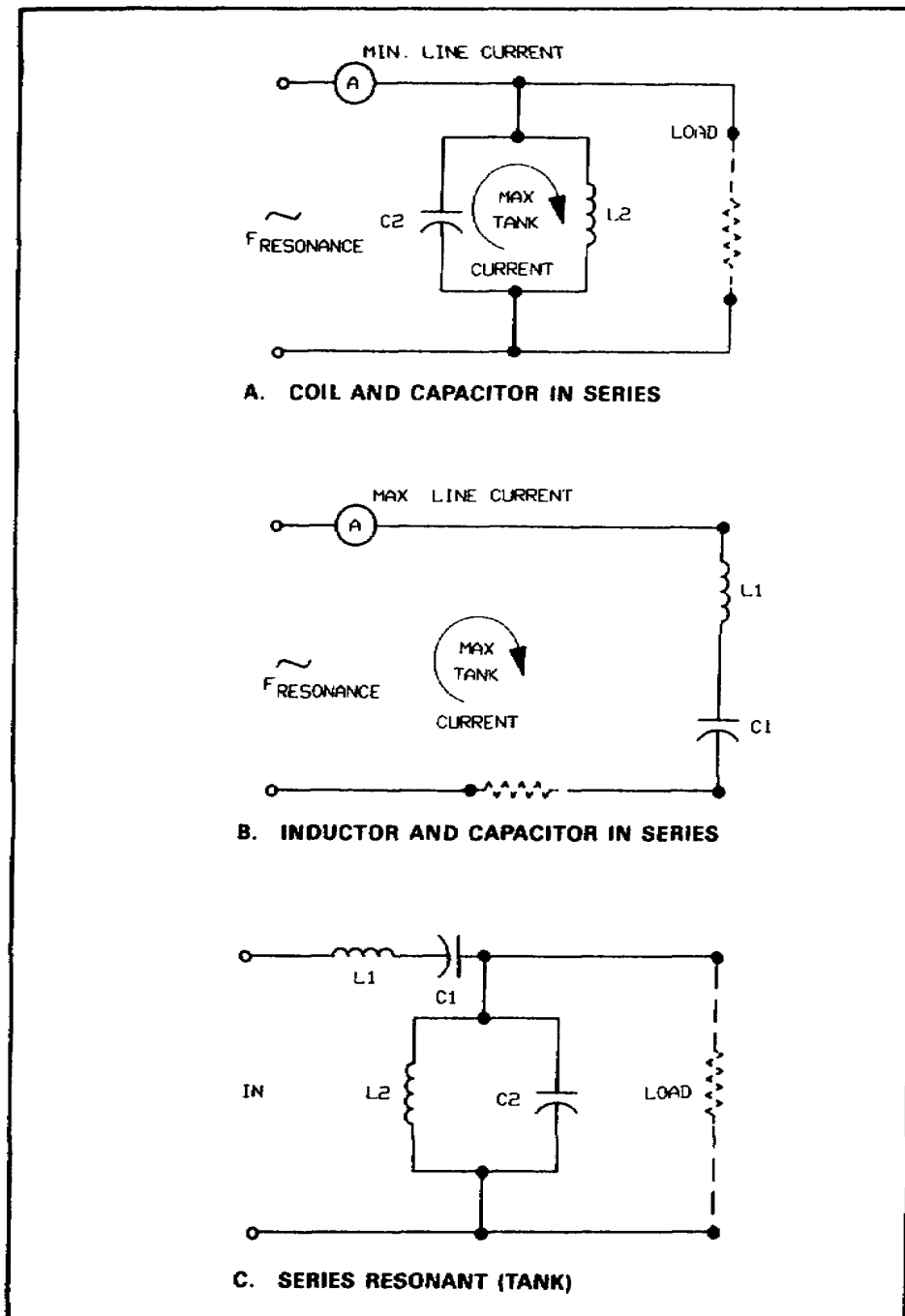


Figure 2-9. L-Section, Band-Pass Filter

T-section. Tank circuits (figure 2-10), connected in series, improve the filtering action by reducing the opposition to the desired frequency. Thus, L_1 - C_1 and L_2 - C_2 work together to deliver current to the load between f_1 and f_2 , while L_3 and C_3 short to ground those currents above and below the cutoff frequencies.

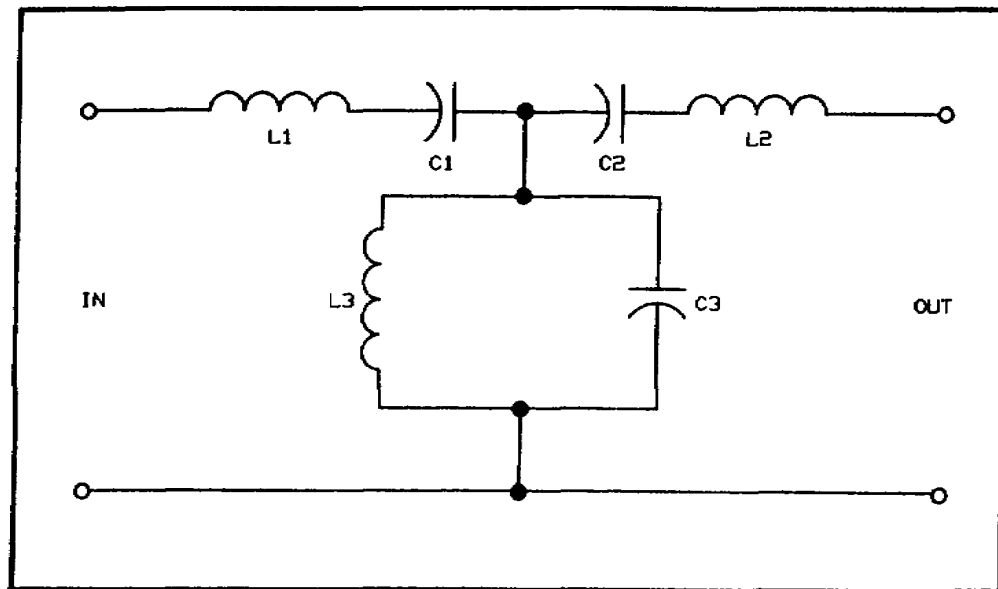


Figure 2-10. T-Section, Band-Pass Filter

π -section. Inductor L_1 and capacitor C_1 are selected to transmit freely between f_1 and f_2 (frequencies) and permit the desired frequency currents to reach the output (figure 2-11). The parallel circuits shunting the load are tuned to either side of f_1 and f_2 to provide an easy path to ground for all other frequencies. The designer of this circuit has the option of tuning L_2 - C_2 below f_1 and L_3 - C_3 above f_2 , or vice versa.

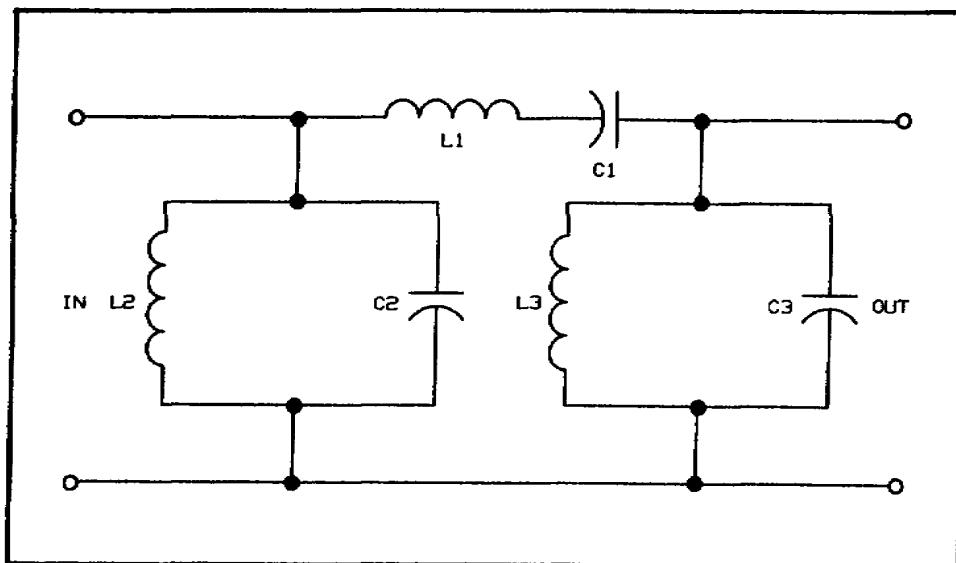


Figure 2- 11. π -Section, Band-Pass Filter.

Transmission Characteristics. By using resonant circuits, it is possible to achieve combinations of the outputs previously discussed (figure 2-12). The single, cutoff frequency of the low-pass and high-pass filters overlap and provide the designer with two cutoff frequencies. The pass band between f_1 and f_2 can be varied to a very narrow bandwidth.

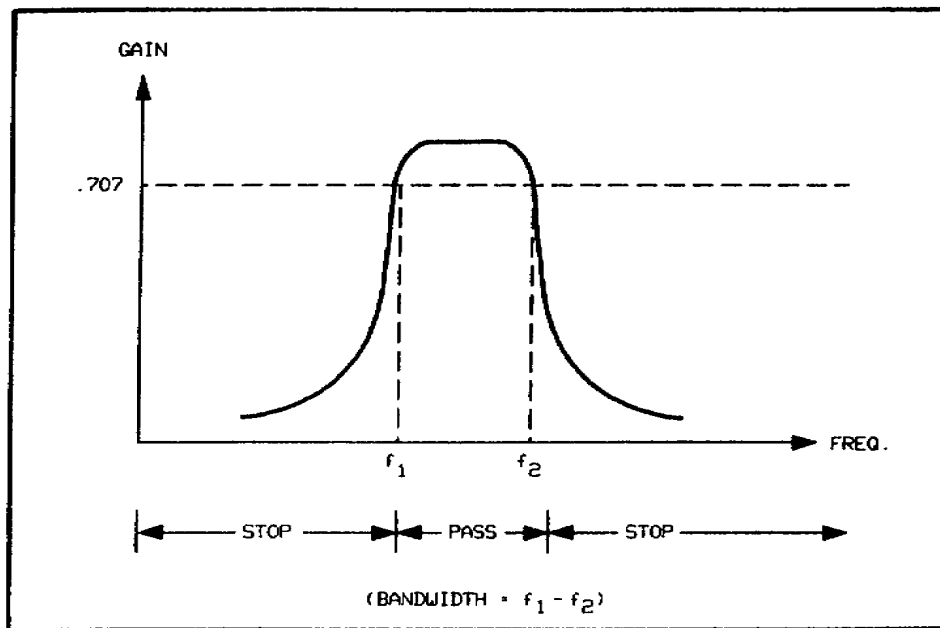


Figure 2-12. Transmission Characteristics of Band-Pass Filters.

Band-Rejection Filters

Band-rejection filters may be used to remove a specific band of objectionable frequencies, such as static interference, from a transmitter that is interfering with television reception.

L-section. The parallel-tuned circuit (L_1 - C_1) and the series-tuned circuit (L_2 - C_2) are tuned to the band frequencies to be rejected (figure 2-13). The

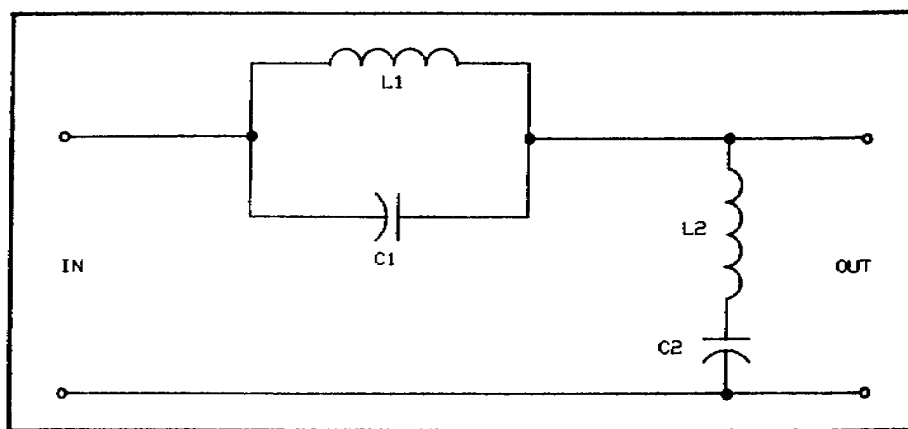


Figure 2-13. L-Section Band-Rejection Filter

undesirable frequencies find a low impedance path through the series-tuned circuits and a high impedance path through the parallel-tuned circuits. Thus, the undesirable band of frequencies are rejected or suppressed. The narrow band of desired frequencies find a high impedance path through the series-tuned circuit and a low impedance path through the parallel-tuned circuit, which is passed on to the load.

T-section. In this circuit, undesired frequencies that manage to get past the first parallel-tuned circuit find a high impedance path toward the load and a low impedance path through the series-tuned circuit to ground (figure 2-14).

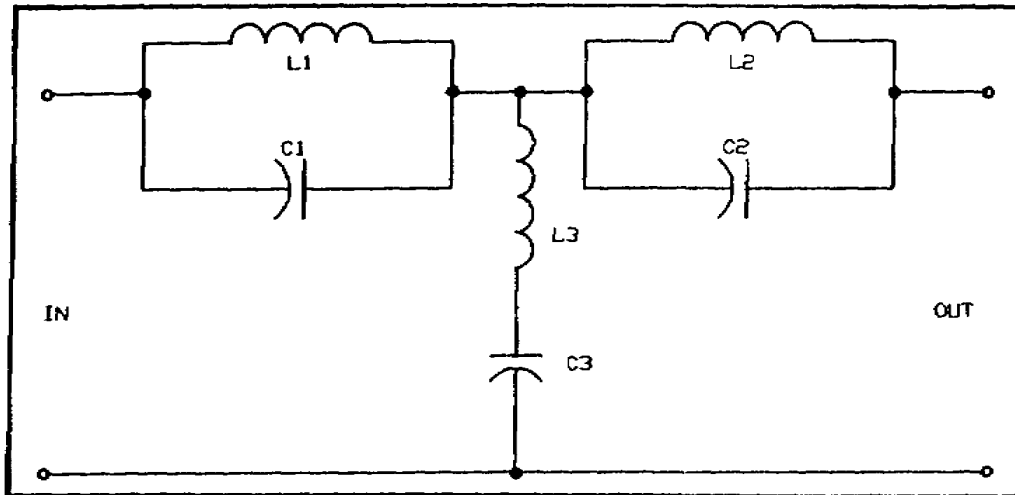


Figure 2-14. T-Section Band-Rejection Filter

π -section. This series-tuned tank circuit (figure 2-15) has maximum line current flow at the resonant frequency, and the parallel-tuned tank has minimum current flow in the line at resonance. The combination of a parallel and two shunting series tanks makes an easy path to ground for undesirable frequency currents. The π -section filter with carefully selected components, can reject a very narrow band of frequencies, because, as with all filters, the more tanks, the sharper will be the sides of the pass band.

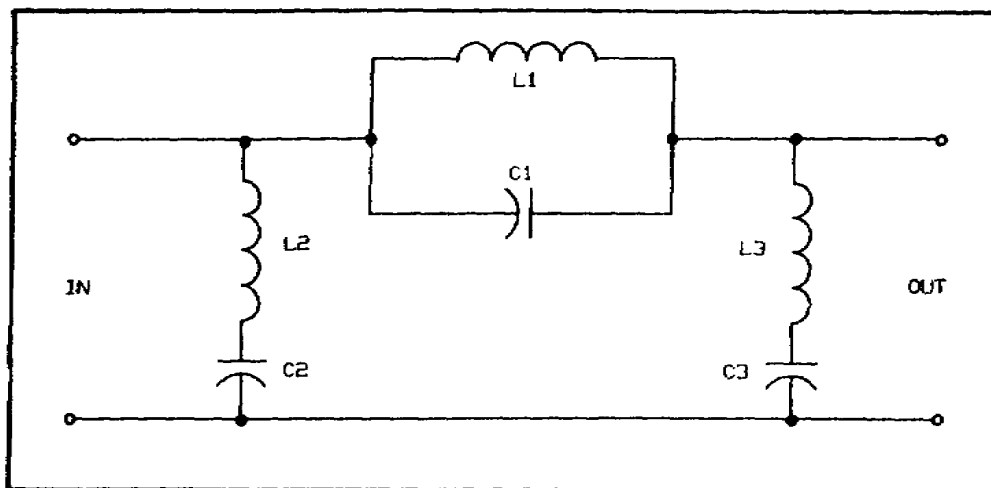


Figure 2-15. π -Section Band-Rejection Filter.

Transmission Characteristics. Once again, rearrangement of circuit components measurably affects the resultant output. Although f_1 and f_2 could remain the same, the pass and stop bands of figures 2-12 and 2-16 are reversed by a change in circuit configuration.

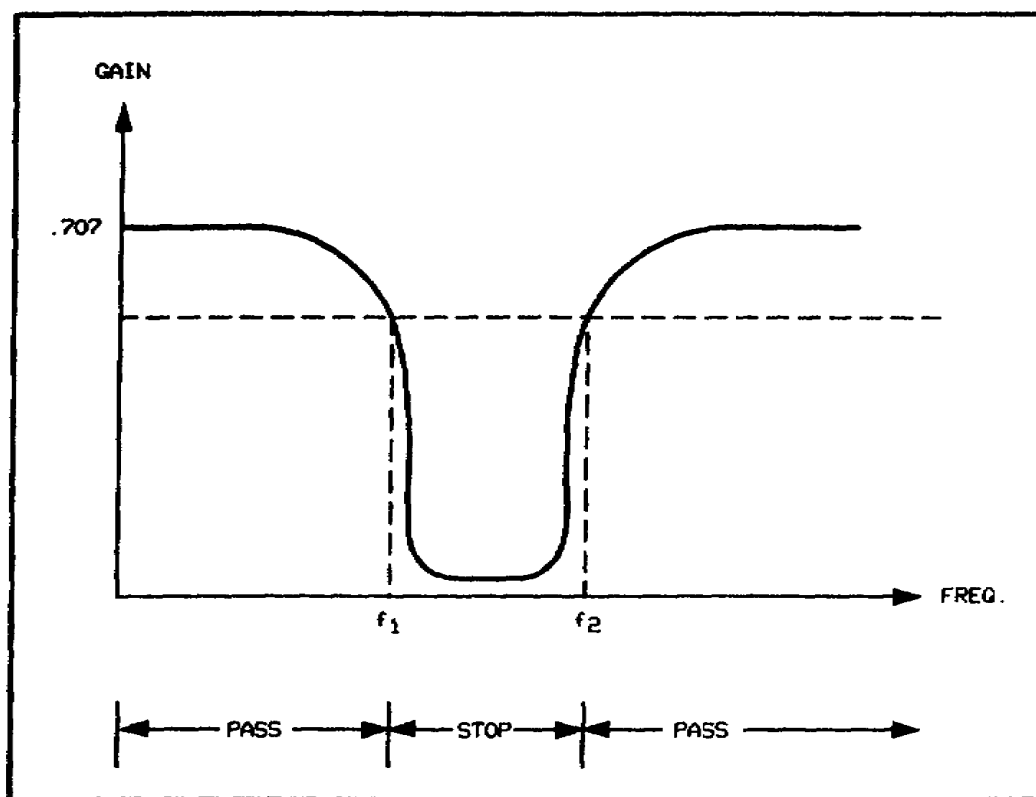


Figure 2-16. Transmission Characteristics of Band-Rejection Filters.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. Which combination of arms is in a full π -section filter?
 - a. One shunt and one series.
 - b. One shunt and two series.
 - c. Two shunts and one series.
 - d. Two shunts and two series.
2. How will an increase in frequency affect a filter circuit?
 - a. Increase capacitive reactance.
 - b. Decrease and increase capacitive reactance.
 - c. Increase inductive reactance.
 - d. Decrease and increase inductive reactance.
3. Where are low-pass filters commonly used?
 - a. Power supplies.
 - b. Coupling networks.
 - c. Amplifying networks.
 - d. Wave-shaping networks.
4. Why is a capacitor connected across the resistor in an RC filter circuit?
 - a. To prevent DC from entering the B+ supply.
 - b. To prevent AC from entering the B+ supply.
 - c. To provide a path for DC.
 - d. To provide a path for AC.
5. What is the function of a capacitor in a high-pass filter circuit?
 - a. It offers a high-impedance path to high-frequency currents.
 - b. It offers a high-impedance path to the desired frequencies.
 - c. It provides a low-impedance path for high-frequency currents.
 - d. It provides a low-impedance path for the undesired frequencies.
6. What BEST describes a parallel resonant tank circuit of a band-pass filter at resonance?
 - a. Has maximum line current through tank.
 - b. Has minimum line current through tank and maximum tank current.
 - c. Has minimum tank current
 - d. Has maximum line current through tank and minimum tank current.

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7. What frequency has been reached if attenuation increases very rapidly?
- Cutoff.
 - Saturation.
 - Resonant.
 - Emergency.
8. To which band of frequencies are the series and parallel resonant circuits in a band-rejection filter tuned?
- At those that are not desired.
 - Above those that are not desired.
 - Below those that are not desired.
 - Above and below those that are not desired.
9. What is the purpose of L_3 - C_3 in the T-section of the band-pass filter in figure 2-17?
- To match the input and output impedances.
 - To match the input and output currents.
 - To short the desired frequency to the reference.
 - To short undesired frequencies to ground.

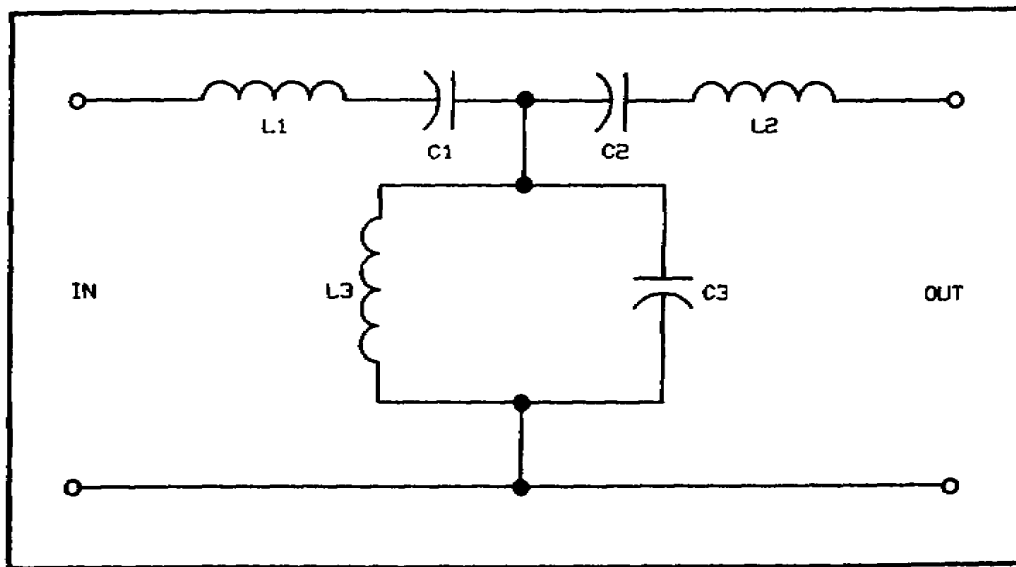


Figure 2-17. T-Section Filter.

10. Which condition describes the L-section, low-pass filter load with respect to its source?
- Capacitance in series and inductance in parallel.
 - Inductance in series and capacitance in parallel.
 - Capacitance and inductance in series.
 - Capacitance and inductance in parallel.

11. How will a high-pass filter be affected if circuit components are interchanged?
 - a. Cutoff frequency will increase.
 - b. Cutoff frequency will decrease.
 - c. Stop and pass bands will widen.
 - d. Stop and pass bands will reverse.
12. What occurs when MORE tank circuits are added to a filter network?
 - a. The pass band sides become broader
 - b. The pass band sides become sharper
 - c. The current at the source increases.
 - d. The current at the source decreases.
13. Which is NOT considered when designing a filter circuit?
 - a. Porousness of the filter.
 - b. Limited circuit flow in the load circuit.
 - c. Passing and rejecting desired frequencies.
 - d. Attenuation of the signal by the filter.
14. What is the normal procedure for constructing a receiver power supply filter?
 - a. Select a cutoff frequency well above the operating frequency.
 - b. Select a cutoff frequency well below the ripple frequency.
 - c. Select a cutoff frequency well below the operating frequency.
 - d. Select a cutoff frequency well above the ripple frequency.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed three or more questions, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 3 GENERATORS AND MOTORS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to explain the purpose and function of AC and DC motors and generators and describe their uses.

Conditions. You will have this subcourse book and work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lesson 1, 2, and 4 (answer 23 of the 30 questions correctly).

DC GENERATORS AND MOTORS

Generators

The basic DC generator is similar to the basic AC generator except in the system of taking the output from the rotating coil. In the AC generator, the rotating coil is connected to the external circuit by the sliprings that convey the AC current in the coil to the external circuit. In the DC generator, the rotating coil is connected to the external circuit by a device called a commutator. The commutator converts the AC current from the rotating coil to current that flows in a single direction through the external circuit.

A commutator is a metal ring (usually copper) that is divided into a number of segments. These segments are insulated from each other and from the shaft upon which they and the rotating coil are mounted. In the basic generator shown in figure 3-1A, the commutator consists of two segments separated by air, with each segment connected to one side of the rotating coil. Two brushes, mounted on opposite sides of the commutator, bear on its surface so that electrical contact is made between the coil and the external circuit.

Figure 3-1A shows the commutator positions during one revolution of the coil. For coil positions a through e, the current in the rotating coil flows in the direction indicated by the arrows and undergoes the changes in magnitude shown by the corresponding points on the curve in figure 3-1B. Verify this by using the left-hand rule for generators. At position e, the coil has completed one alternation, and the induced voltage is zero.

During the second alternation, the coil sides cut the field in the opposite direction. Current flow is thus reversed as shown in figure 3-1B. This means that at the moment when the current in the coil sides changes its direction, the commutator segments reverse their connections to the brushes. It also means that the current flow through the load is in the same direction during the second alternation as it was during the first alternation. This is indicated by points e to i on the curve in figure 3-1B.

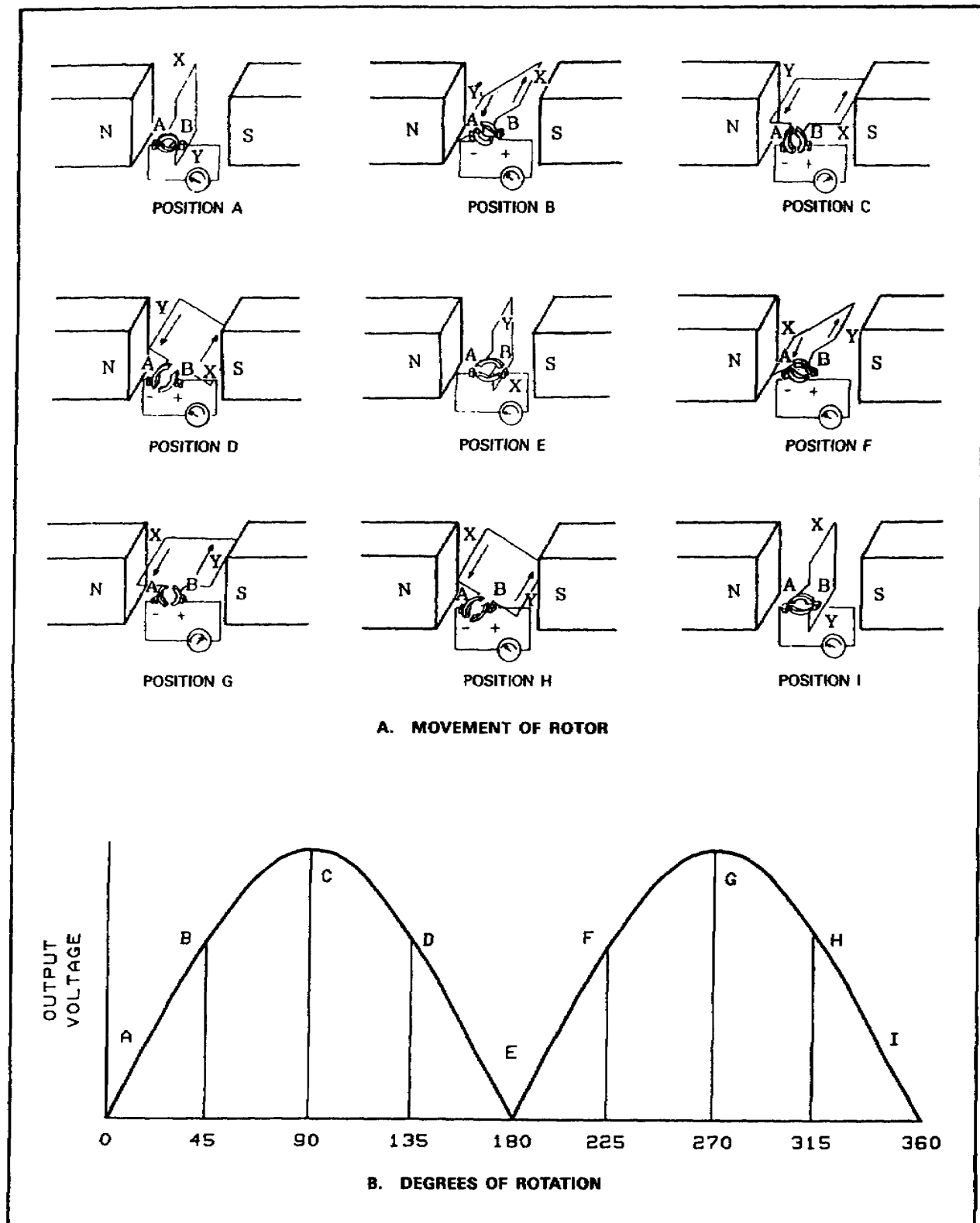


Figure 3-1. Simple DC Generator

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In a DC generator, the current flow in the rotating coil reverses in direction, however, the current flow in the external load is constantly in one direction because of the action of the commutator. To reduce the amount of fluctuation in the external current, the moving part of a DC generator is composed of a large number of coils arranged at different angles about the axis. These coils are all connected to the commutator. The commutator has as many pairs of segments as there are coils. The group of coils is called the armature.

Field Magnets. The magnetic field in which the coil rotates can be produced by permanent magnets or electromagnets called field magnets. Permanent magnets are used only in small machines (magnetos). Since it is possible to produce electromagnets which are much stronger than any permanent magnet, electromagnets are used in all large generators and in most small ones.

The electric current necessary to excite a field magnet is occasionally supplied by some outside source such as a battery or other generator, which is separately excited. More commonly current from a generator is used in the field coils of such a generator. The current in a DC generator can be used to excite the field coils, but all AC generators must have fields separately excited by an auxiliary DC generator.

Classification of Generators. Self-excited generators are classed according to the three general types of field connections they employ: series, shunt, and compound. Compound generators are further classified as cumulative-compound and differential-compound.

Series. In the series-connected generator, all of the current from the generator is passed through the field windings because the external circuit and the field are in series (figure 3-2).

Shunt. Another way to excite the field magnets is to connect them in parallel with the load (See figure 3-3). This type of generator is commonly called a shunt generator. Because the current in the field windings is wasted as far as the useful load current delivered to the external circuit is concerned, the

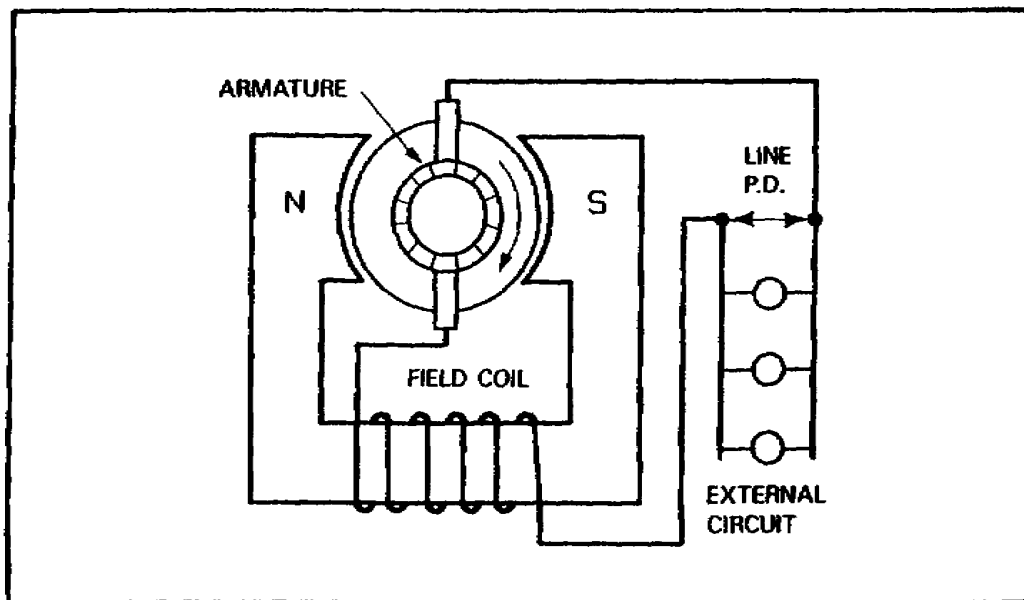


Figure 3-2. Series Generator.

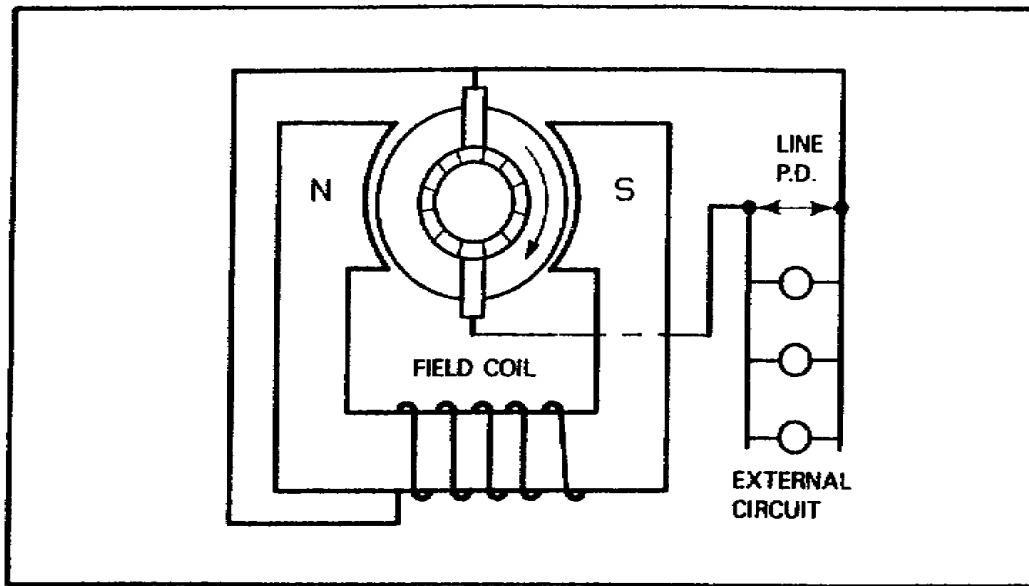


Figure 3-3. Shunt Generator.

field current is made as small as possible. So that the field magnets may be sufficiently excited by a small current, they are wound with many turns of wire.

In a cumulative-compound generator both series and shunt fields are used. The shunt field is usually the stronger, but, since both contribute to the magnetic field, they aid each other. When the load increases, the armature voltage decrease and the voltage applied to the shunt field decreases. The increased load current flowing through the series increases its field. By proportioning the two fields so that the series fields compensate for the undesirable effects of the armature and shunt fields, the output voltage may be kept constant.

In a differential-compound generator, the two fields are wound so that they oppose each other; that is, the magnetic field of the series field is in opposite direction to that of the shunt field. For any increase in load, there is an increase in the strength of the series field. Also, because its direction is opposite to the shunt field, the total combined field strength is decreased. Therefore, the output voltage decreases as the load increases. Differential-compound generators are used in welding equipment where the output terminals are sometimes short circuited.

From these general types of generators, engineers have developed many modifications to satisfy particular requirements and to increase generator efficiency.

Motors

A machine that changes electrical energy into mechanical energy is called a motor. Around any current-carrying conductor, a magnetic field exists whose strength depends on the amount of current. A current-carrying conductor (supplying electrical energy), when placed in a magnetic field, has a force exerted on the conductor which causes it to move out of the field (mechanical energy) (figure 3-4). In this figure, you can see that a current-carrying conductor in a magnet field tends to move at right angles to the field. If a coil

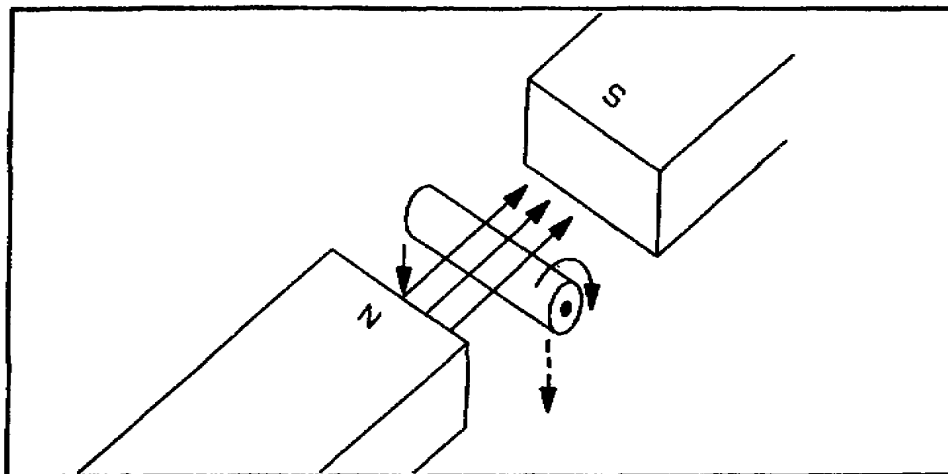


Figure 3-4. Current-Carrying Conditions in a Magnetic Field.

is suspended in a magnetic field, as shown in figure 3-5A, a zero torque (turning effect) is exerted on the coil. The forces acting on the coil sides tend to separate them. In figure 3-5B, the forces acting on the coil sides produce a torque which reaches its maximum at position in figure 3-5C. If the current in the coil were reversed at the proper moment, a continuous rotating force would be developed. This current is changed by a commutator. If this simple coil is in the zero-torque position when the current is connected, it will not start.

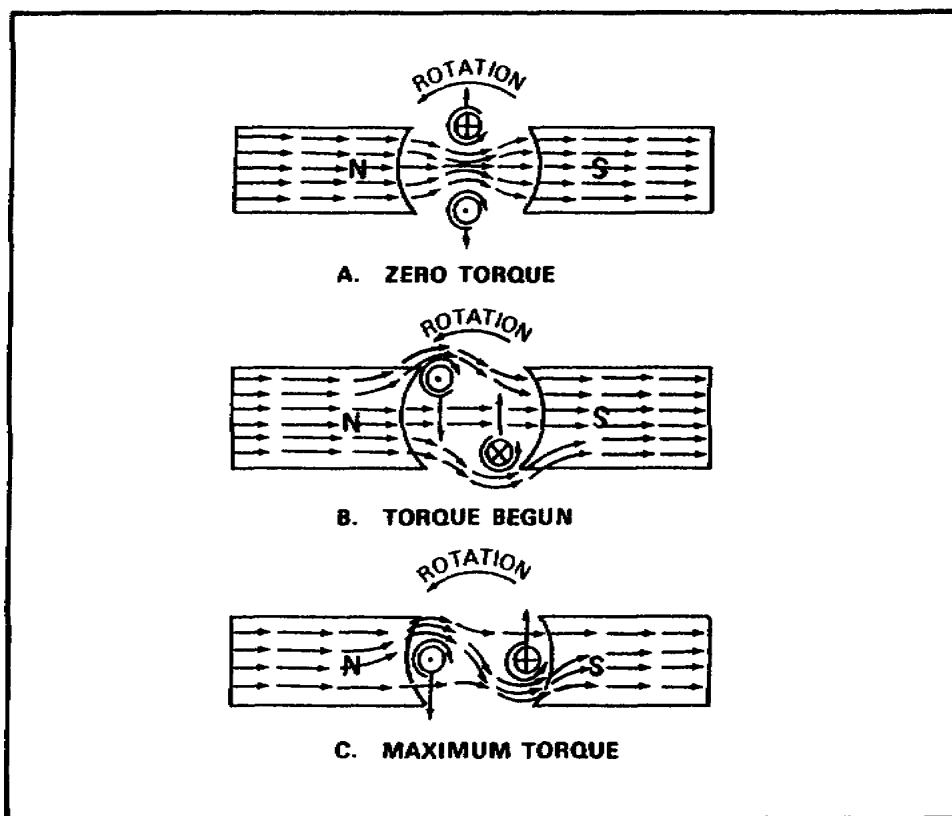


Figure 3-5. DC Motor, Showing Positions on the Current-Carrying Coil.

If another coil is added at an angle of 90° (figure 3-6) from the original coil (figure 3-5), the coil assembly will then turn regardless of its position. In figure 3-6, coil CD has a torque applied to it in a clockwise direction. As it rotates, it turns the commutator. This turns coil AB and as coil CD moves toward its neutral position, the current is conducted into coil AB by the commutator. The continuation of this cycle reverses the current in CD so that it continues to receive a force in clockwise direction.

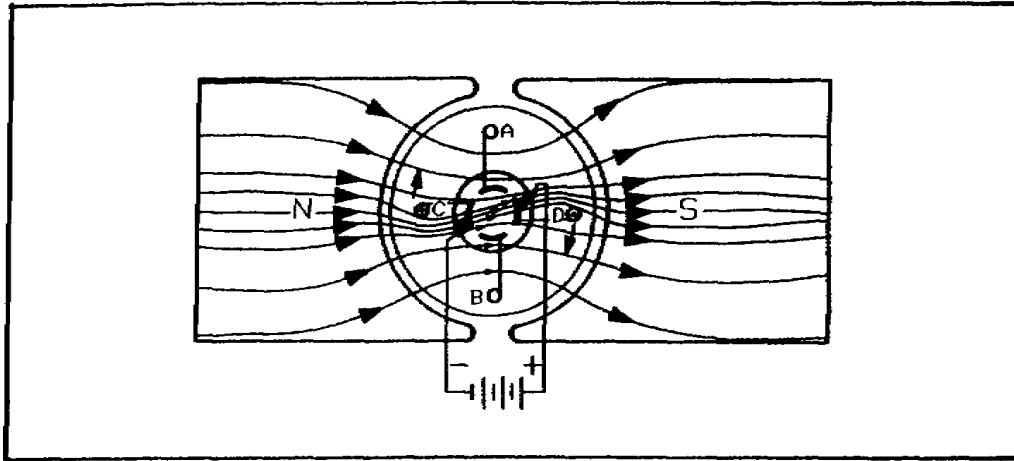


Figure 3-6. T-Section, High-Pass Filter.

The rotational force which turns the armature is called torque. Torque in a motor depends on two factors: the current flowing in the armature conductors and the flux density of the field. Mathematically, this relationship is expressed as: $T = 0 \times I_A$, where T is torque, 0 (ϕ) is flux density, and I_A is armature current.

Series DC Motor

In the series DC motor, the armature and field are connected in series as shown in figure 3-7. This method of connection requires that the field windings be large enough to carry heavy armature current. Consequently, the wire in a series field is large and the winding contains few turns. The one serious disadvantage of the series motor is that if its load is disconnected, it will race to destruction because the motor speed varies inversely with the load. Therefore, this type of motor is not good for constant-speed applications. It is ideal where it is continuously under the control of an operator and where a high starting torque is required.

The torque of a series motor varies as the square of the current. That is, if the current could be doubled in the armature while the field flux remained constant, the torque would be doubled. Also, if the current remained constant in the armature and the field current were doubled, the torque would be doubled. Since the field and armature are in series, the current in both must be the same; therefore, with each winding contributing twice as much torque, there is four times as much torque in the combination. (The torque will increase as the square of the current, up to the point where the core material reaches saturation.) Because of its speed characteristics, the series motor is not suitable for any load where the required torque might drop below 15 percent of full-load torque.

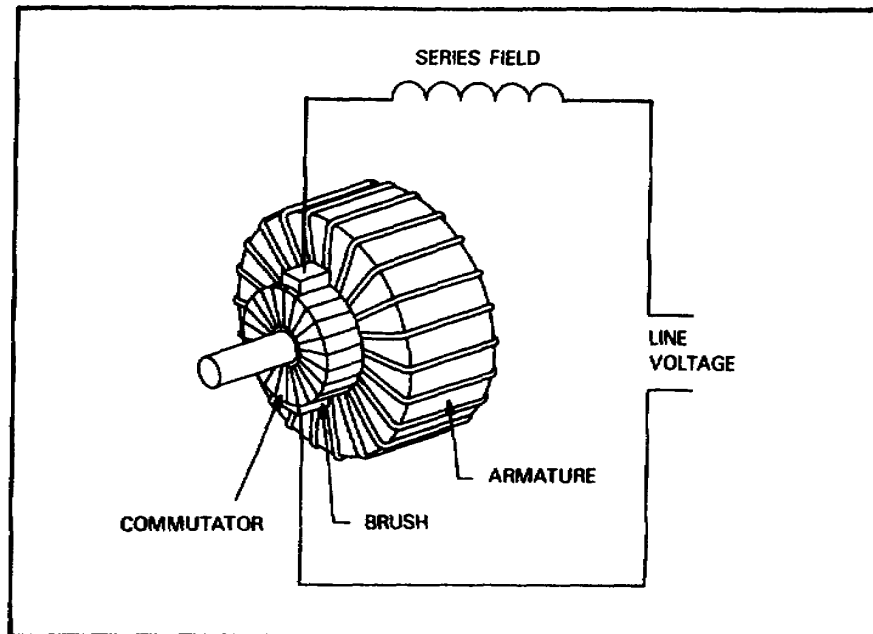


Figure 3-7. Series DC Motor.

Shunt Motor. In the shunt motor, the field winding is connected in parallel with the armature (figure 3-8). There are two circuits through the shunt motor; one through the armature and one through the field coil. The field coils are wound with relatively small wire and have a large number of turns. This type of winding is necessary to maintain a high flux magnetic field

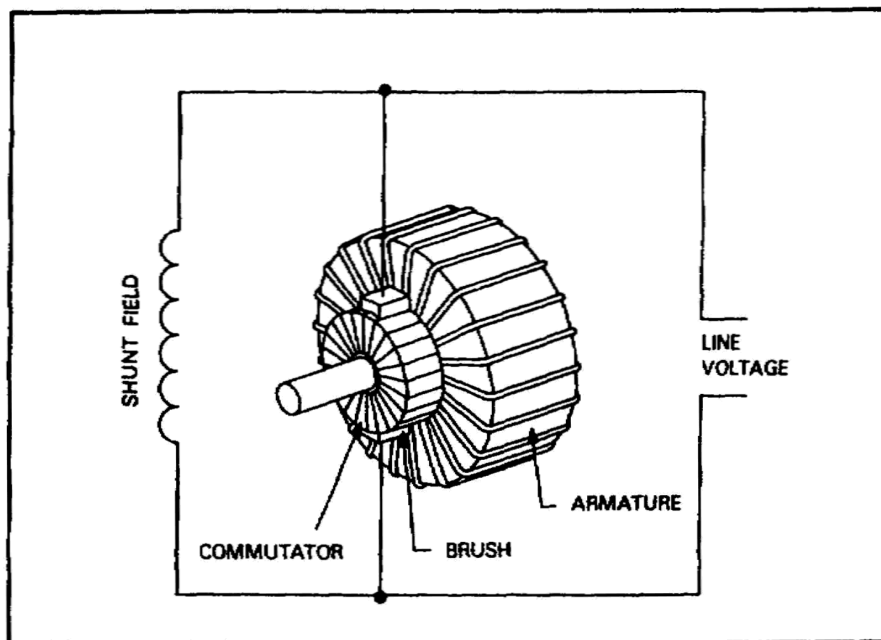


Figure 3-8. Shunt Motor.

value and to prevent coil overheating. Because the field is connected across the powerline, the density of the magnetic field remains constant. Therefore, the torque of a shunt motor must vary with the current in the armature; that is, if the armature current doubles, the torque also doubles. Since the magnetic field strength is constant, the motor speed will be constant from no load to full load.

Actually, the motor speed may vary up to 10 percent but this is considered negligible. The shunt-wound motor is a constant-speed type, but, because of fixed field current, it does not have as high a starting torque as the series motor.

Compound Motors. There are two kinds of compound DC motors, cumulative and differential. A typical compound motor is in figure 3-9.

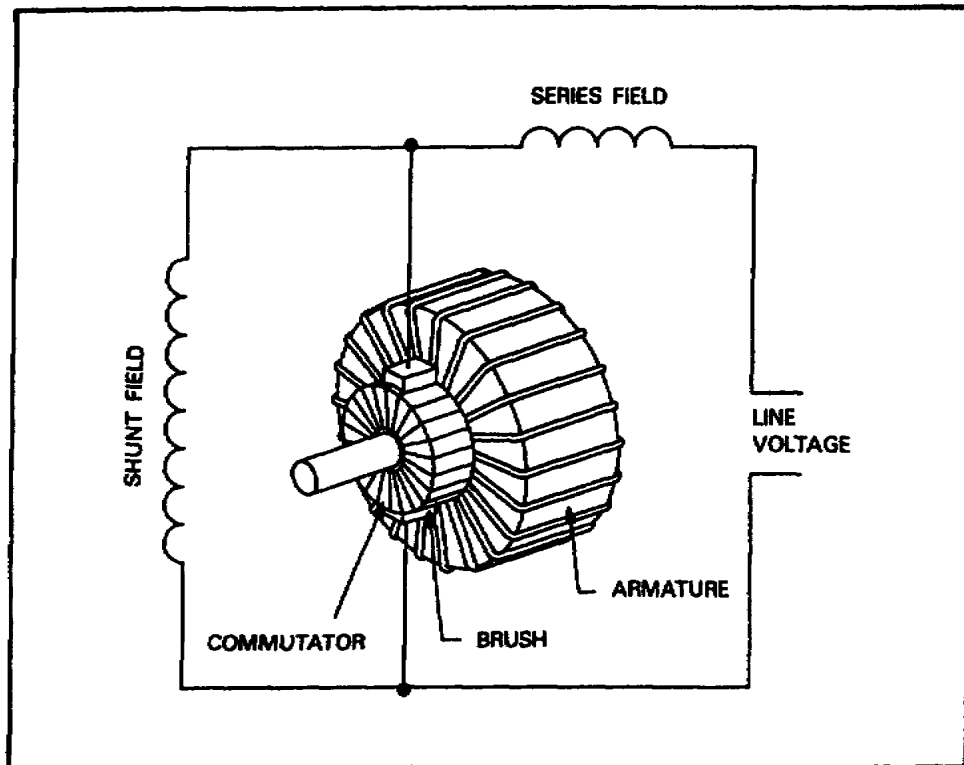


Figure 3-9. Compound Motor.

Cumulative. Cumulative compound motors employ both series and shunt windings. The windings are connected so that the series winding aids the shunt field. Characteristics of this motor lie somewhere between those of a series and those of a shunt. By properly proportioning the two fields, the speed of the motor can be made relatively constant under varying load conditions.

Differential. In a differential-compound motor, the fields are arranged so that the series field opposes the main shunt field. This weakens the main field and tends to increase the speed of the motor as the load is increased. Differential compounding is not used much because it produces instability, especially when the series field is very strong.

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Speed Regulation. Speed regulation concerns change in speed with change in applied load torque, other conditions remaining constant. Such changes in speed, as occur under these conditions, are due to inherent properties of the motor and should not be confused with speed changes effected through manipulation of rheostats or other speed control devices.

The speed regulation of a motor is generally understood to mean the change in speed with changes in load. It is usually expressed as a percentage, as in the following equation.

$$\text{P Regulation} = \frac{\text{No load speed} - \text{full load speed} \times 100}{\text{Full load speed}}$$

Reversing the Direction of Rotation. The direction of rotation of a motor can be reversed by changing the direction of current flow in either the field or armature, but not in both. Reversing the direction of the magnetic field and also reversing the direction of current in the armature would leave the direction of the torque unchanged. For this reason, a DC motor will run on alternating current.

The universal motors used on many household appliances, which will run on either DC or AC, are simply small DC (generally series) motors. It is not a good idea to connect a DC motor to an AC source and vice versa.

Motor Starters. The armature current of a motor, which is comparatively small at its normal running speed, is very much larger as the motor is starting and picking up speed. If the armature coils were wound with large enough wire to safely carry the heavy starting current, the armature would have to be much larger and heavier. This would reduce the efficiency of the motor. Actually, motor designers select the gage of wire to suit the small currents which flow in the armature when the motor is running at its normal speed. A motor starter protects the armature coils from damage while the motor is gaining speed.

The motor starter is a variable resistance, connected in series with the armature. It limits the flow of current through the armature when the armature is running slowly. The motor is switched on with the maximum resistance in the circuit. As the armature speeds up, the starter handle moves a little at a time cutting out some resistance at each step. Finally, all the resistance is removed and the motor has reached its running speed without damage.

AC GENERATORS AND MOTORS

Generators

AC generators are classified according to what revolves, the armature or the field. They are also classified as to the number of phases of current used; single and multiple.

Revolving-armature. In a revolving-armature AC generator, the stator provides a stationary electromagnetic field. The rotor, acting as the armature, revolves in the field, cuts the lines of force, and produces the desired output voltage. In this generator, the armature output is taken through sliprings and thus retains its alternating characteristic.

The revolving-armature AC generator is seldom used. Its primary limitation is that its output power is conducted through sliding contacts (sliprings and brushes), which are subject to frictional wear and sparking. In addition, they are exposed and thus liable to arc-over at high voltages. Consequently, revolving-armature generators are limited to low-power and low-voltage applications.

Revolving-field. The revolving-field AC generator (figure 3-10) is by far most widely used. In this generator, DC from a separate source is passed through windings on the rotor by means of sliprings and brushes. This maintains a rotating electromagnetic field of fixed polarity (similar to a rotating bar magnet). The rotating magnetic field, following the rotor, extends outward and cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings since magnetic fields of first one polarity and then the other cut through them. Since the output power is taken from stationary windings, the output may be connected through fixed terminals directly to the external loads as through terminals T1 and T2 in the figure. This is an advantage because there are no sliding contacts; the whole output circuit is continuously insulated, thus minimizing the danger of arc-over.

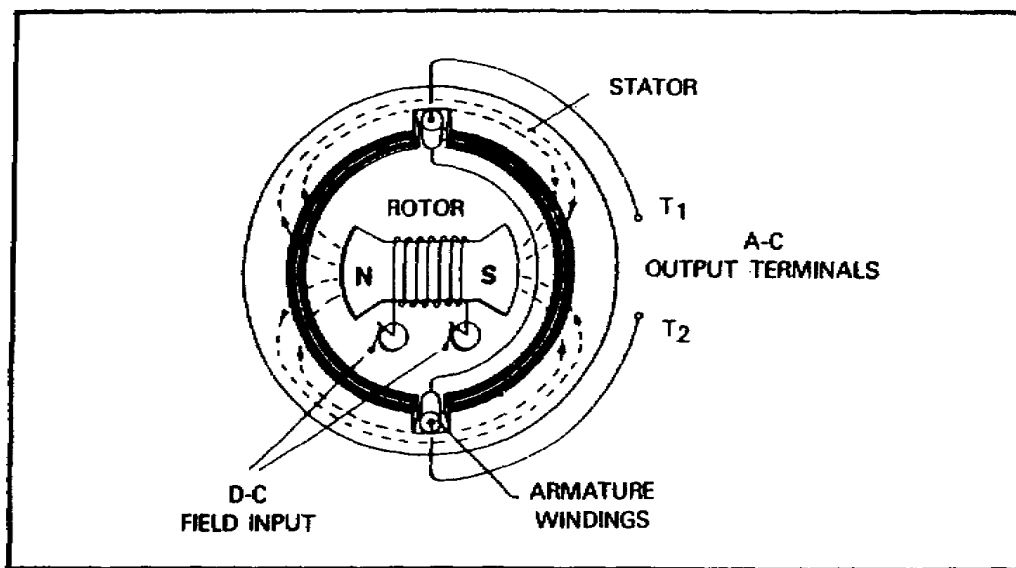


Figure 3-10. Rotating-Field AC Generator.

Sliprings and brushes are used on the rotor to supply DC to the field. They are used because the power level in the field is much lower than in the armature circuit.

Rating of Generators: Volt-Amperes, Power Factors, and Power. From studying inductance and capacitance, you know that, in some AC circuits, voltage and current are not always in phase and that there may be various leading and lagging phase relations between voltage and current. In AC generators, because alternating voltages and currents are continually varying in a sinewave manner, it is possible that the voltage and current waves may not be in phase. Whether the voltage and current of any AC circuit are in phase or out of phase depends upon the type of circuit elements forming the load of the circuit.

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Volt-amperes. In DC circuits, where the value of the voltage and current are constant, the product of volts and amperes is equal to the power in watts ($P = E \times I$). In AC Circuits, the product of volts and amperes is equal to the power in watts only, when the volts and amperes are in phase. When the voltage and current are out of phase, the product of the volts and amperes is greater than the watts consumed by the circuit. For this reason the product of volts and amperes is called the volt-amperes (VA) of the circuit. This product is also frequently called the apparent power of a circuit.

$$VA = V \times \text{amp or } VA = E \times I$$

Power Factor: The ratio of the actual watts consumed by a circuit to the VA of that circuit is called the power factor thus

$$\text{Power factor} = \frac{\text{Actual power}}{\text{Apparent power}},$$
$$\text{or PF} = \frac{P}{E \times I}.$$

The value of the power factor may vary from 0 to 1.

Power: The actual power consumed by a circuit may be calculated by the following equation.

$$P (W) = E(V) \times I (\text{amp}) \times PF$$

AC generators are rated in terms of VA or Kilovolt-ampere (KVA) output, at a specified frequency and power factor. For example, a single-phase 60 Hz AC generator rated at 100 KVA would deliver 100 KW of power with a load producing a power factor of 1. This same generator would provide 80 KW of power with a load at 80-percent power factor. The maximum load rating of a particular generator is determined by the internal heat it can withstand. As the power factor goes down, more and more current is required to pass through the generator windings in order to provide the same amount of voltage (power out). The 100 KVA generator, required to supply a 100 KVA load at 20-percent power factor would most assuredly have excessive heating in the generator field windings because of the required increase in DC field current needed to maintain the required power output. Power companies strive to keep the power factor of their load as high as possible in order to obtain the best generating efficiency for their system. Power companies often give special rates to large commercial users who maintain loads with high power factors.

Basic Functions of Generator Parts. Almost all rotating-field AC generators are actually two generators in one. A typical machine consists of an AC generator and a smaller DC generator built into a single unit (figure 3-11). The output of the AC generator supplies alternating current to the load for which the generator was designed. The DC generator's only purpose is to supply the DC needed to maintain the generator field. This DC generator is referred to as the exciter.

Any rotary generator requires a prime moving force (figure 3-11-B1) to rotate the AC field and exciter armature. This rotary force is transmitted to the generator through the rotor drive shaft and is usually furnished by a combustion engine, turbine, or electric motor. The exciter shunt field (2) creates an area of intense magnetic flux between its poles. When the exciter armature (3) rotates in the exciter field flux, voltage is induced into the exciter

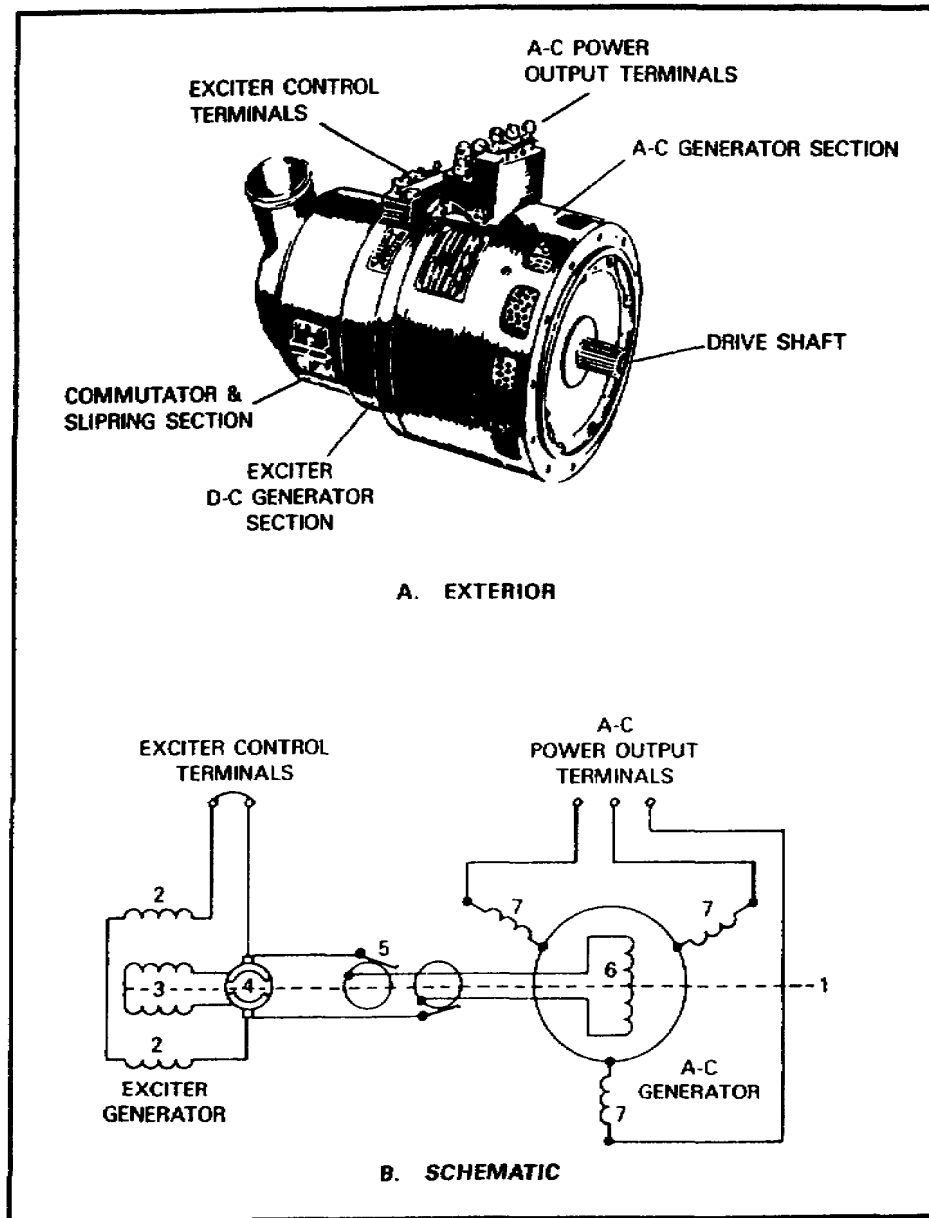


Figure 3-11. AC Generator.

armature windings. The exciter output commutator and brushes (4) connect the exciter output directly to the AC generator field input sliprings and brushes (5). Since these sliprings, rather than a commutator, are used to supply current through the AC generator field (6), current will always flow in one direction only through these windings. Thus, a fixed polarity magnetic field is maintained at all times in the AC generator field windings. When the AC generator field is rotated, its magnetic flux is passed through and across the AC generator armature windings (7). Remember, a voltage is induced into a conductor if it is stationary and a magnetic field is passed across the conductor, the same as if the field is stationary and the conductor is moved. The alternating voltage induced in the AC generator armature windings is connected through fixed terminals to the AC load.

Single-Phase Generators. A single-phase AC generator (figure 3-12) has a stator made up of a number of windings in series which form a single circuit in which an output voltage is generated. The principle of the single-phase AC generator is described first, and the polyphase AC generator is described later.

Figure 3-12 is a schematic diagram of a single-phase AC generator having four poles. The stator has four polar groups evenly spaced around the stator frame. The rotor has four poles with adjacent poles of opposite polarity. As the rotor revolves, AC voltage is induced in the stator windings. Since one rotor pole is in the same position relative to a stator winding as any other pole, all stator polar groups are cut by equal amounts of magnetic lines of force at any given time. As a result, the voltages induced in all the windings have the same amplitude (value), at any given instant. The four stator windings are connected to each other so that the AC voltages are in phase ("series aiding"). Assume that rotor pole one, a south pole, induces a voltage in the direction indicated by the arrow in stator winding one. Since rotor pole two is a north pole, it will induce a voltage in the opposite direction in stator winding two with respect to that in winding one.

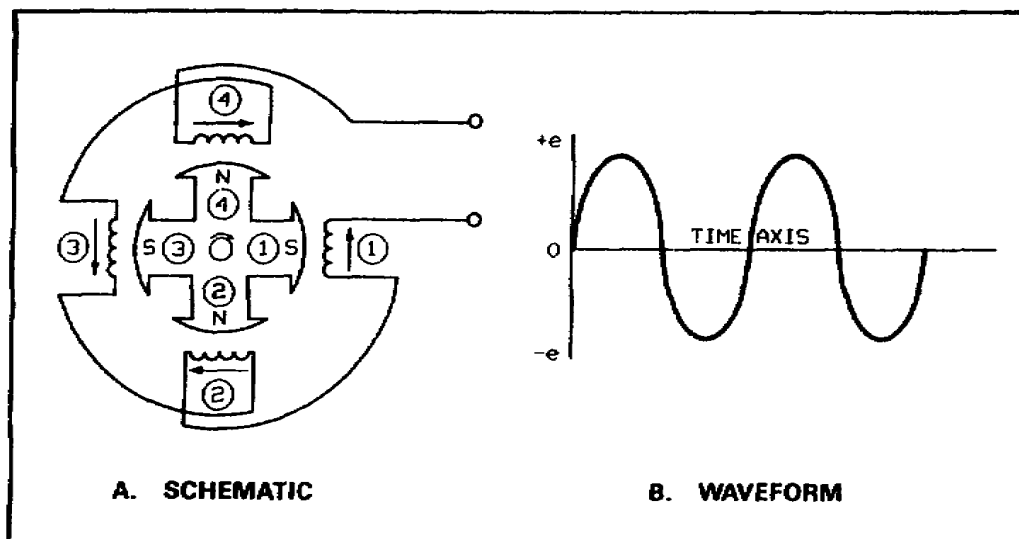


Figure 3-12. Single-Phase AC Generator.

In order that the two induced voltages be in series addition, the two coils are connected as shown. Applying the same reasoning, the voltage induces in stator winding three (clockwise rotation of the field) is in the same direction (counterclockwise) as the voltage induced in coil one. Similarly, the direction of the voltage induced in winding four is opposite to the direction of the voltage induced in winding one. All four stator winding groups are connected in series so that the voltages induced in each winding add to give a total voltage that is four times the voltage in any one winding.

Multiphase Generators. Multiphase AC generators have two or more single-phase windings symmetrically spaced around the stator. In a two-phase AC generator, there are two single-phase windings physically spaced so that the AC voltage induced in one is 90 degrees out of phase with the voltage induced in the other. The windings are electrically separate from each other. When one winding is being cut by maximum flux, the other is

not being cut by flux. This condition establishes the 90° relation between the two phases. Figure 3-13 is a schematic diagram of a two-phase, four-pole, AC generator. The stator consists of two signal-phase windings (phases) completely separated from each other. Each phase is made up of four windings which are connected in series so that their voltages add. The rotor is identical to that used in the single-phase AC generator. In figure 3-13A, the rotor poles are opposite all of the coils in phase A. Therefore, the voltage induced in phase A is maximum, and the voltage induced in phase B is zero. As the rotor continues rotating in a clockwise direction, it moves away from the windings of phase A and approaches those in phase B. As a result, the voltage in phase A decreases from its maximum value and the voltage in phase B increases from zero. In figure 3-13B, the rotor poles are opposite the windings of phase B. Now the voltage induced in phase B is maximum, and the voltage induced in phase A has dropped to zero. Notice that in the four-pole AC generator, a 45° mechanical rotation of the rotor corresponds electrically to one quarter cycle, or 90° electrical. Figure 3-13C illustrates the waveforms of the voltage generated in each of the two phases. Both are sine curves, and A leads B by 90° .

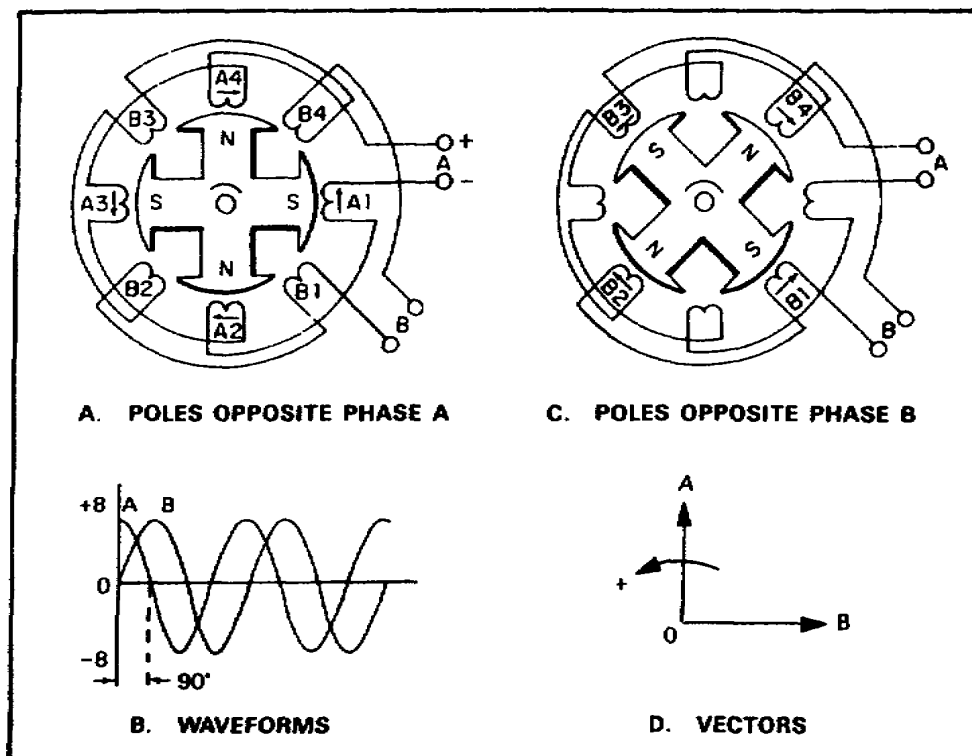


Figure 3-13. Two-Phase, Four-Pole AC Generator.

The three-phase AC generator, as the name implies, has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. A schematic diagram of a three-phase stator showing all the coils becomes so complex, it is difficult to see what is actually happening. A simplified schematic diagram, showing all the windings of a single phase lumped together as one winding, is in figure 3-14A. The rotor is omitted for simplicity. The waveforms of voltage are shown to the right of the schematic. The three voltages are 120° apart and

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are similar to the voltages that would be generated by three single-phase AC generators whose voltages are out of phase by angles of 120° . The three phases are independent of each other.

Y Connection. Rather than have six leads come out of the three-phase AC generator one of the leads from each phase may be connected to form a common junction. The stator is then Y connected. The common lead may not be brought out of the machine. If it is brought out, it is called the neutral lead. The simplified schematic (fig 3-14B) shows a Y-connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, R_{AB} is connected across phases A and B in series, and R_{BC} is connected across phases B and C in series. Thus, the voltage across each load is larger than the voltage across a single phase. In a Y-connected AC generator, the three start ends of each single-phase winding are connected together to a common neutral point, and the opposite, or finished, ends are connected to the line terminals A, B, and C. These letters are always used to designate the three phases of a three-phase system or the three line wires to which the AC generator phases connect.

Delta Connection. Another configuration for the stator of a three-phase AC generator is the delta connection. The delta-connected stator is shown in figure 3-14C. Each load is connected across one phase in the delta connection, while in the Y connection each load is across two phases. For this reason, the delta connection delivers less voltage to the load than does the Y connection.

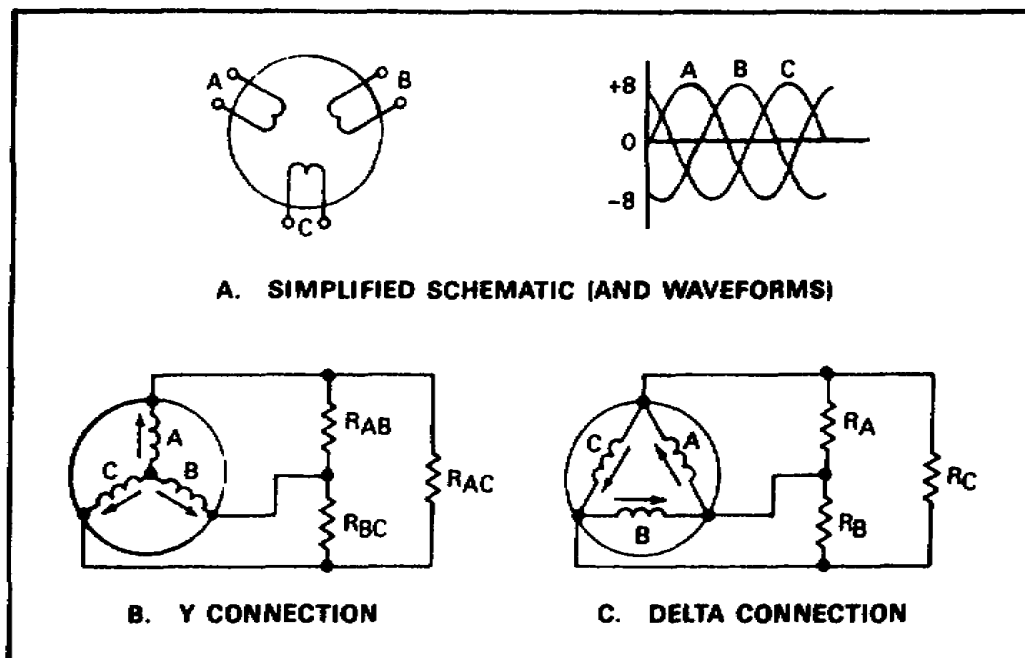


Figure 3-14. Three-Phase AC Generator.

Frequency. The frequency of the AC generator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency; the lower the speed, the lower the frequency. The more poles there are on the rotor, the higher the frequency for a given speed. When a rotor has rotated through an angle such that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle.

The more pairs of poles there are for any given frequency, the lower the speed of rotation. A two-pole generator rotates at twice the speed of a four-pole generator for the same frequency of generated voltage. The frequency is expressed by the equation

$$f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

where P is the number of poles and N the speed in rpm. For example, a two-pole, 3,600 rpm generator has a frequency of

$$\frac{2 \times 3,600}{120} = 60 \text{ Hz};$$

a four-pole, 1,800 rpm generator has the same frequency. A six-pole, 500 rpm generator has a frequency of

$$\frac{6 \times 500}{120} = 25 \text{ Hz};$$

and a twelve-pole, 4,000 rpm generator has a frequency of

$$\frac{12 \times 4,000}{120} = 400 \text{ Hz}.$$

Motors

AC motors use the same basic principle of operation as DC motors. That principle involves putting electrical energy into the motor by current flow in the armature (which is located in a magnetic field) and taking mechanical energy from the rotating armature. The rotation of the armature is caused by the interaction of the fields about the armature windings and the field winding. The armature's rotation is mechanically transmitted to the motor's load.

AC motors operate from an AC source. There are three general types: induction, series, and synchronous. The induction motor may be further described according to the type of armature used; squirrel-cage induction motor, or wound-rotor induction motor.

Induction Motor. An induction motor makes use of the transformer principles explained in the next lesson. A primary winding is connected to the power source and is mounted on the stator. The secondary winding is mounted on the rotor. The current in the primary winding causes a magnetic field to surround the winding. This field about the primary passes through the secondary winding causing a current in the secondary. Recall that this action of a primary winding current causing a secondary winding current is called induction.

The induction motor is the most widely used AC motor. Its design is simple, and its construction is sturdy. It has no commutator, so it is much more trouble-free than a DC motor. Although it is usually used where the speed must be constant, small induction motors (less than one hp) can also operate efficiently at variable speeds. Induction motors have revolving fields and can be single phase or polyphase (more than one). The operating principles are the same in either case, except that single-phase motors require special starting windings. Single-phase induction motors vibrate a great deal because their torque (turning force) is pulsating rather than continuous.

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Series Motor. AC series motors have the same characteristics as DC series motors. They have a stationary field and a commutated armature winding and both windings are in series. The series motor is a variable speed motor with low speeds for heavy loads and high speeds for light loads. These motors are noted for their light weight in relation to the power delivered. They are well suited for portable devices such as power tools.

Synchronous Motors. The speed of a synchronous motor is controlled by the frequency of the AC power source which drives it. It is synchronized or in time with this frequency. In order that its speed may be left constant, a synchronous motor is regulated to a high degree of accuracy. These motors are used for timing devices such as meters that record the time which equipment has been used.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What produces a DC output from a generator?
 - a. Field winding.
 - b. Commutator.
 - c. Alternator.
 - d. Armature winding.
2. Why are electromagnets, rather than permanent magnets, normally used in large generators?
 - a. To provide a stronger magnetic field.
 - b. To provide a stronger electrostatic field.
 - c. For more economy.
 - d. For more durability
3. Which generator provides its own field current?
 - a. Separately excited AC generator.
 - b. Separately excited DC generator.
 - c. Self-excited DC generator.
 - d. Self-excited AC generator
4. In which generator does the total current pass through the field windings?
 - a. Cumulative-compound.
 - b. Differential-compound.
 - c. Shunt.
 - d. Series.
5. What is the purpose of the large number of turns that are required on the shunt generator field winding?
 - a. To increase the armature speed.
 - b. To reduce current drained from the load to a minimum.
 - c. To decrease the armature speed.
 - d. To increase current drained from the load to a maximum.

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6. What is the ratio of field current to armature current in a series DC motor?
- a. 1:1.
 - b. 2:1.
 - c. 3:1.
 - d. 4:1.
7. How is the torque of a series DC motor affected if the armature current is reduced by one-half?
- a. Increased by one-fourth.
 - b. Reduced by one-half.
 - c. Increased by one-half.
 - d. Reduced by three-fourths.
8. How many current paths are provided in the DC shunt motor in figure 3-15?
- a. One.
 - b. Two.
 - c. Three.
 - d. Four.

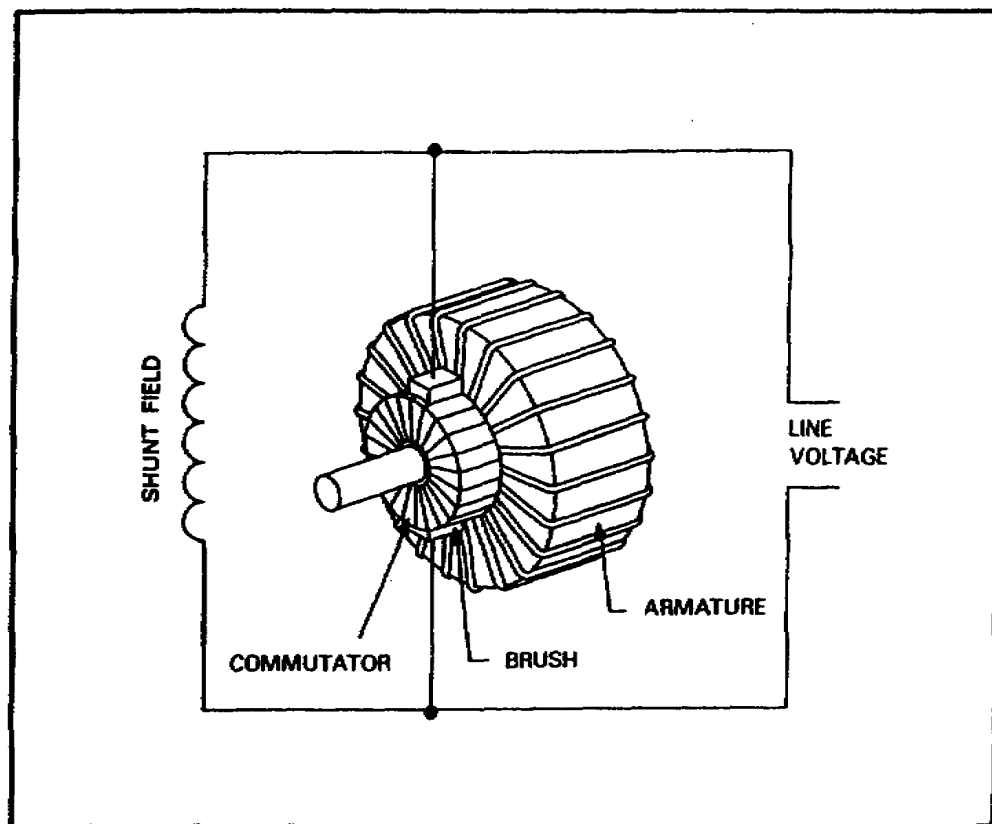


Figure 3-15. DC Shunt Motor.

9. How is the torque of a shunt DC motor affected if the armature current is doubled?
- Halved.
 - Reduced by one-eighth.
 - Increased by one-fourth.
 - Doubled.
10. What characterizes a DC shunt motor?
- Constant speed.
 - Varying speed and constant torque.
 - Constant torque.
 - Varying torque and varying speed.
11. What is the formula for generator frequency?
- $$f = \frac{PN}{120}.$$
 - $f = PN \times 120.$
 - $$f = \frac{PN}{60}.$$
 - $f = PN \times 60.$
12. What is the difference, in degrees, between windings of a three-phase generator?
- 45.
 - 60.
 - 90.
 - 120.
13. How many rpm must a four-pole AC generator make in order to generate an output frequency of 60 Hz?
- 1,100.
 - 1,600.
 - 1,800.
 - 2,200.
14. Which motor is normally used for timing devices?
- DC series.
 - AC series.
 - Compound.
 - Synchronous.

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15. What is the most widely used AC motor?

- a. Induction.
- b. Series.
- c. Shunt.
- d. Compound.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solution. If you missed four or more questions, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 4

TRANSFORMERS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to explain the purpose and function of transformers and describe their use, as well as the use of reflected impedance matching and the losses and turns ratio.

Conditions. You will have this subcourse book and work without supervision.

Standards. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 2, and 3 (answer 23 of the 30 questions correctly).

USE

One of the most common electrical devices used in radio and radar equipment is the transformer. This device is used to transfer energy from one circuit to another. Some of the results are impedance matching, phase shifting, voltage step-up or step-down, current step-up or step-down, frequency selection, and isolation of circuits.

Transformers are also designed and used to accomplish specific jobs. Your understanding of the actions of a transformer is of considerable importance.

BASIC PRINCIPLES

Recall your study of electromagnetism and inductance, in Basic Electricity, Part I. You learned that a wire or coil in which current is flowing has a magnetic field about it; you also learned that the amount of current determines the relative strength of that magnetic field. Another factor is that if a magnetic field cuts through a conductor, a voltage will be induced in the conductor. These important facts are the bases of the principles of transformer operation.

With two conductors parallel to each other as in figure 4-1, the magnetic field caused by the current flowing through circuit P sweeps across circuit S inducing a voltage in it. You can apply the terminology used in discussing transformers to explain this simple circuit. Call circuit P the primary since it is from this source that the magnetic field is produced. Call circuit S the secondary because it is in this circuit that a voltage is being induced.

When the switch in the primary is closed, the current starts to flow and build up rapidly from zero to its maximum value. This produces a rapidly expanding magnetic field around the primary. Remember that motion is necessary in order to have an induced voltage. The motion in this case is the expanding field which cuts the secondary loop, inducing a voltage in it. This

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induced voltage, however, is an instantaneous action. When the current in the primary has reached its maximum value, the resultant magnetic field is at its maximum strength. The field, under this condition, is neither expanding from nor collapsing back into the primary loop. This being the case, the flux is not cutting the secondary loop, and no voltage is induced in it. This does not mean that the magnetic field is not present. The magnetic field is still there, since it is being sustained by the current flow in the primary. As long as the current flows at a steady rate, the flux about the conductor is maintained at a steady strength, neither expanding nor collapsing, resulting in no field motion and no induced voltage.

Notice in figure 4-1, the instantaneous voltage that is induced in the secondary when the circuit is closed is of opposite polarity to the voltage in the primary.

In figure 4-1, what can you expect when the switch in the primary is opened? First of all, since the circuit is broken, current will cease to flow. Since the magnetic field about the primary was dependent on the current to sustain it, the field must necessarily collapse. As the field collapses back into the primary, it again cuts through the secondary, this time in the direction opposite to that when it was expanding. This motion again induces a voltage in the secondary. Since the field is cutting through the secondary loop in the reverse direction, the voltage induced is of the opposite polarity to that induced when the switch is closed.

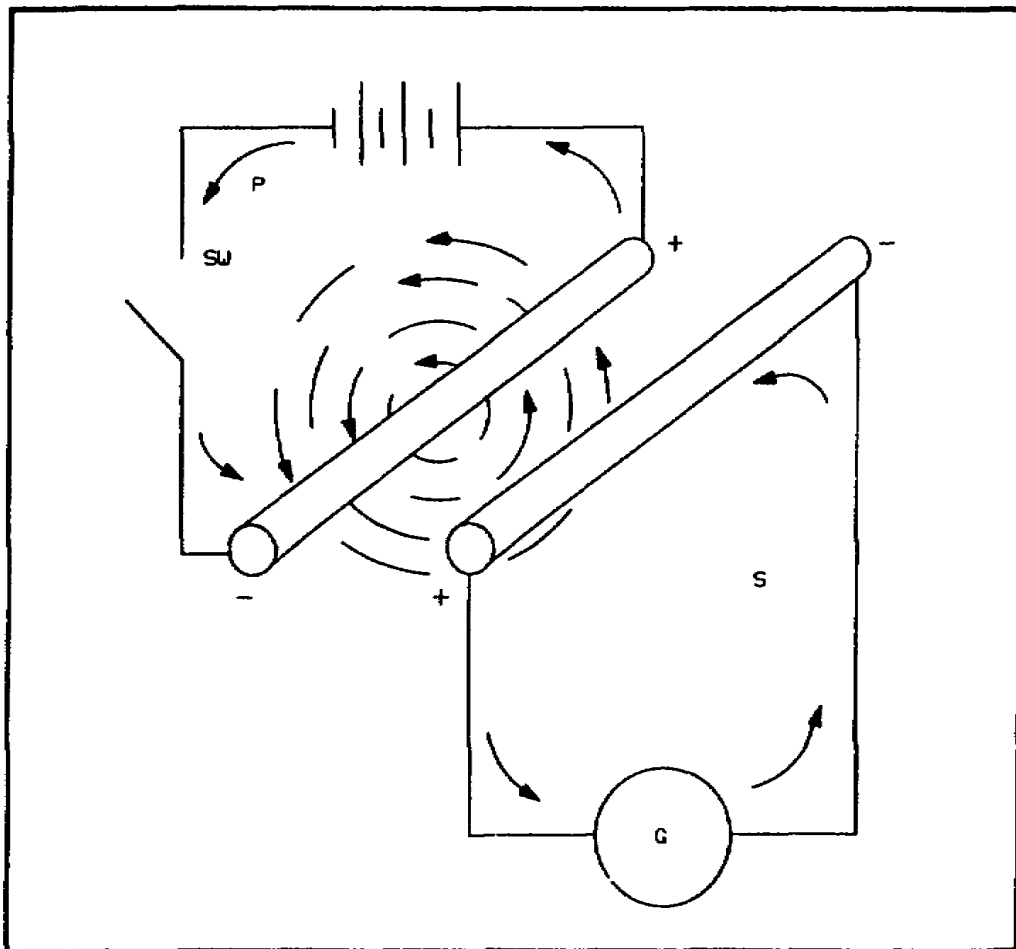


Figure 4-1. Single Loop Transformer.

You can see, then, that a transformer is of little value if you apply pure DC to the primary, since there will be no sustained voltage induced in the secondary. However, if you were to apply pulsating DC or AC, the magnetic field would be constantly building up and collapsing, thus continually inducing a voltage in the secondary.

This method of energy transfer, from one circuit to another, is called *mutual induction*. As a transformer, the single loop of wire in figure 4-1 is a poor device for the transfer of power. The magnetic field about a straight wire is relatively weak, and the secondary offers only a short length of wire in which to have a voltage induced. You can, of course, increase the strength of the magnetic field by winding the primary in the form of a coil. Thus, if the primary and the secondary were wound as coils, the induced voltage would be greatly increased. Even with this refinement, the transformer is still not operating at maximum efficiency. You can see from figure 4-2 that all of the flux building up from the primary does not cut the secondary. This is called flux leakage. It reduces the efficiency of the transformer.

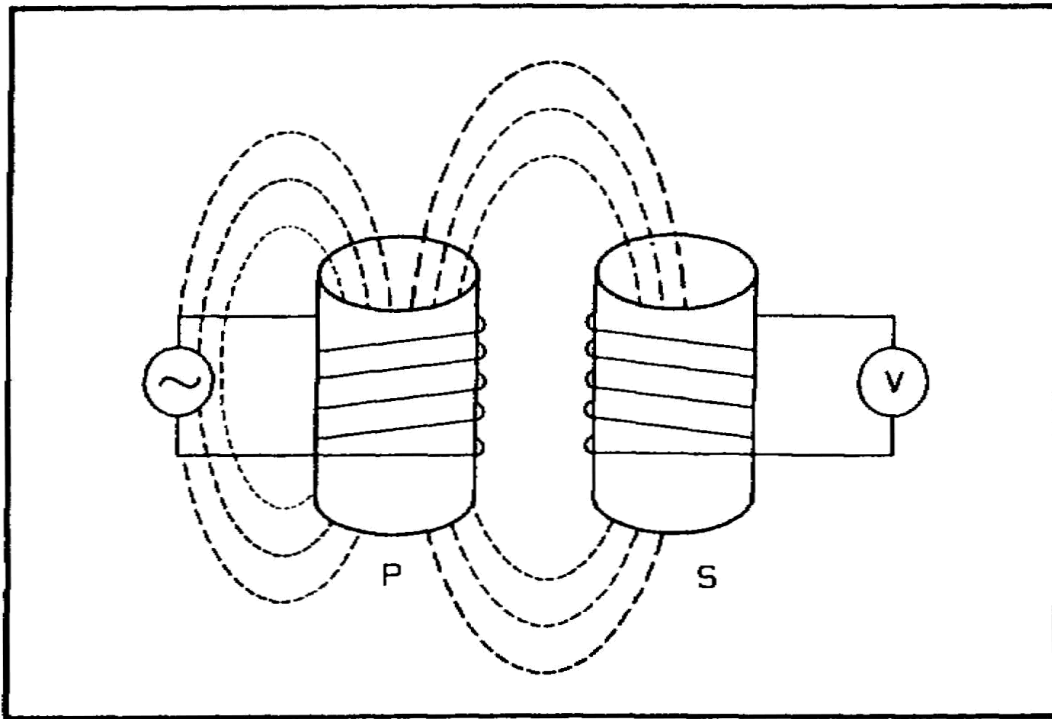


Figure 4-2. Multiloop Transformer

To help reduce flux leakage, a suitable core material can be inserted between the coils. It provides a path of low reluctance (resistance) to the magnetic lines of force. In figure 4-3, the primary has been wound on one leg of an iron core and the secondary has been wound on the other leg. A transformer wound in this manner would still operate at a low efficiency. It is presented here to show how a transformer works.

Transformer Ratios

Voltage and Turns Ratio. An ideal transformer is one that is 100-percent efficient. This means that in each turn of the secondary coil, the flux must set up a back EMF of the same value as each turn of the primary coil. The

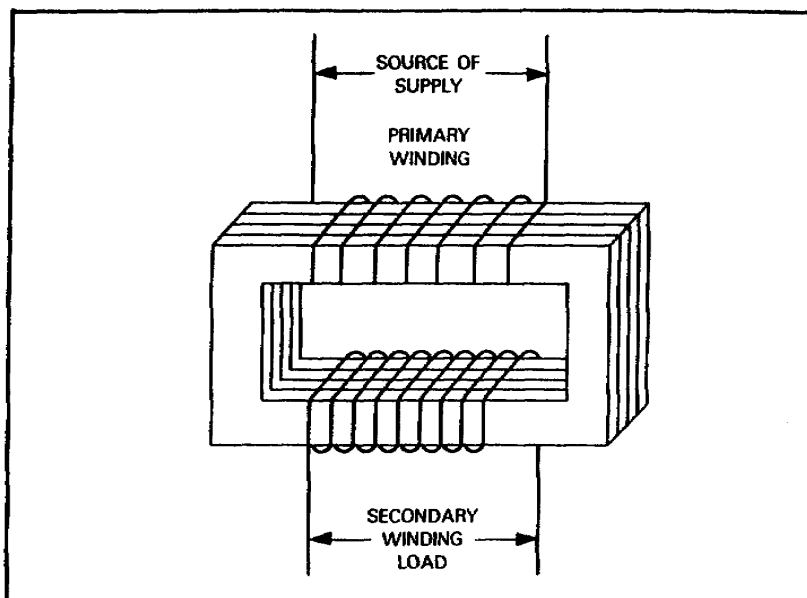


Figure 4-3. Iron Core Transformer

total induced voltage in the secondary coil must be equal to the volts per turn ratio of the primary coil multiplied by the number of turns in the secondary. This may be written:

$$E_s = \frac{E_p}{N_p} N_s.$$

N = Number of turns

s = secondary

p = primary

Solving this equation for the ratio

$$\frac{E_p}{E_s},$$

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}.$$

To illustrate the use of the above formula, take a transformer with a primary winding of 3,000 turns connected to a 240-VAC source and a secondary winding of 300 turns. You can easily calculate the voltage across the secondary from the equation

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}.$$

$$E_s = \frac{E_p}{N_p} N_s$$

$$E_s = \frac{240}{3,000} \times 300$$

$$E_s = 24V$$

The voltage induced per turn in the secondary will be:

$$24 \div 300 = .08\text{V.}$$

$$.08\text{V} \times 3,000 = 240\text{V}$$

The above transformer is said to be a step-down transformer, since from the 240 V applied you are getting only 24 V from the secondary. A step-up transformer then, would be one in which electric energy would come from the secondary at a higher potential than the primary voltage.

Current Ratio. The preceding explanation of transformer operation was considered with an unloaded secondary. If a load is placed on the secondary, there will be current flowing in the secondary. For example, if an AC motor is connected across the secondary terminals of a transformer, the motor draws current. The amount of current depends upon the power required by the motor to perform its work.

Within the transformer, this secondary current tends to magnetize the core in a direction opposite to that of the magnetizing action of the primary current. This magnetizing action of the secondary tends to lower the induced EMF in both the primary and secondary windings. The counter EMF is lowered in the primary circuit, therefore permitting a greater current to flow in the primary.

The load on the secondary is consequently a determining factor of the primary current, considering the proportion of voltage turns previously discussed. Being an ideal transformer, there are no losses and the primary power is equal to the secondary power. This can be expressed as $P_p = P_s$, where P_p is the primary power and P_s is the secondary power. Now,

$$\begin{aligned} P_p &= E_p I_p \text{ and} \\ P_s &= E_s I_s, \text{ so} \\ E_p I_p &= E_s I_s, \\ \text{or } \frac{E_p}{E_s} &= \frac{I_s}{I_p}. \\ \text{Then, } \frac{E_p}{E_s} &= \frac{N_p}{N_s}. \end{aligned}$$

Using the two equations above: $\frac{N_p}{N_s} = \frac{I_s}{I_p}.$

This equation shows the current and turns ratio of an ideal transformer.

Figure 4-4 shows a transformer having a primary winding of 5,500 turns and a secondary of 250 turns, rated at 10 V amps. The primary is connected to a 110-VAC power source. The secondary voltage is found by using the following formula:

$$\begin{aligned} E_s &= \frac{N_s}{N_p} \times E_p, \\ &= \frac{250}{5,500} \times 110, \\ &= 5 \text{ V.} \end{aligned}$$

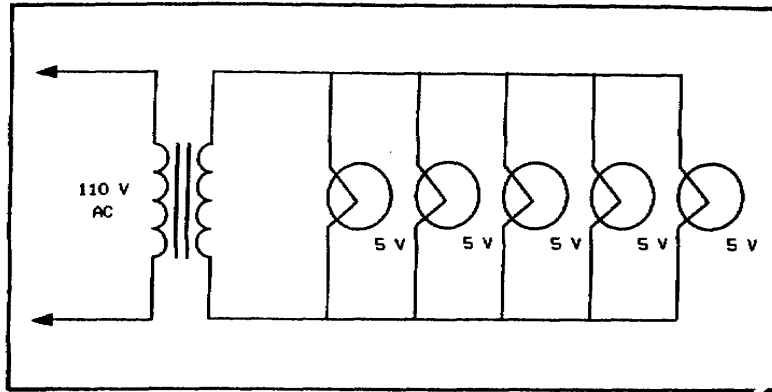


Figure 4-4. 10-V Amps Transformer.

If five vacuum tubes, each drawing 0.12 amps of current, are connected to the secondary, the total secondary current will be 5×0.12 or 0.6 amps. The primary current will be

$$I_p = \frac{N_s}{N_p} \times I_s = \frac{250}{5,500} \times 0.6 = 0.027 \text{ amps.}$$

The energy delivered to and supplied by the primary is: $I_p E_p = 0.027 \times 110 = 2.97 \text{ W}$ or approximately 3 W. As a check, note that each tube takes 0.12 amps at 5 V; each tube is using: $5 \times 0.12 = 0.6 \text{ W}$. Five of these tubes require: $5 \times 0.6 = 3 \text{ W}$.

Since this transformer, which is rated at 10 V-amp (which is 10 W for a resistive load), is delivering only 3 W, it is loaded at: $3 \div 10 \times 100 \text{ percent} = 30 \text{ percent}$ of its rated load.

Impedance Ratio. Impedance (Z) is equal to E divided by I. Therefore,

$$Z_p = \frac{E_p}{I_p}, Z_s = \frac{E_s}{I_s}.$$

the ratio is then

$$\frac{Z_p}{Z_s} = \frac{I_p}{E_s} = \frac{E_p}{I_p} \times \frac{I_s}{E_s}.$$

$$\frac{Z_p}{Z_s} = \frac{E_p}{E_s} \times \frac{I_s}{I_p}$$

Substituting from equations in the second paragraph in this section.

$$\frac{Z_p}{Z_s} = \frac{N_p}{N_s} \times \frac{N_p}{N_s} = \frac{N_p^2}{N_s^2}$$

$$\frac{Z_p}{Z_s} = \left(\frac{N_p}{N_s} \right)^2$$

From this equation, it is evident that the impedance seen at the primary is equal to the load impedance multiplied by the square of the ratio of number of turns in primary to number of turns in secondary.

$$Z_p = Z_s \left(\frac{N_p}{N_s} \right)^2$$

Assume the circuit in figure 4-5 to help clarify the equations above. Figure 4-5 shows a step-down transformer to which 500 V is applied and which has a 10-Ω resistor as a load on the secondary. There is a potential of 50 V at the secondary, and 5 amps of current flow in the circuit.

$$\left(\frac{E_p}{E_s} = \frac{N_p}{N_s} \right); \left(I = \frac{E}{R} \right).$$

There will also be 0.5 amps of current in the primary

$$\left(\frac{N_p}{N_s} = \frac{I_s}{I_p} \right).$$

The impedance in the primary is

$$Z = \frac{E}{I} = \frac{500}{0.5} = 1,000 \, \Omega .$$

(Note that the ratio of Z_p to Z_s is 100 to 1). The impedance ratio of the primary to the secondary is equal to the square of the turns ratio. This fact is used for impedance matching in amplifiers.

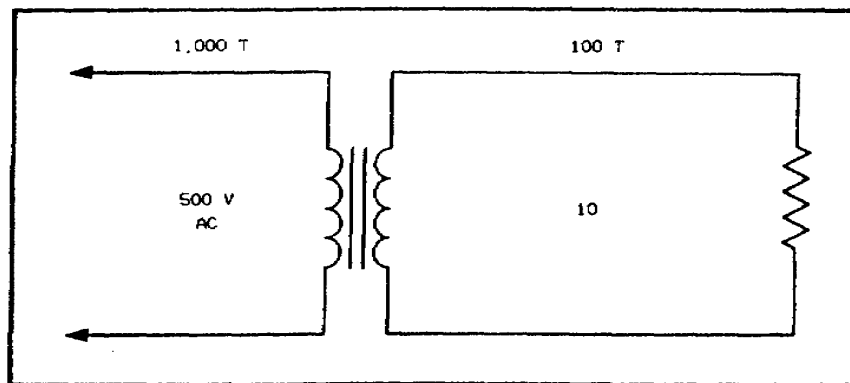


Figure 4-5. Step-Down Transformer.

It is inconvenient to designate a transformer in reference to the turns on each winding by the actual number of turns. The American Society of Electrical Engineers has established a uniform system of transformer designation in this respect. The *turns ratio* of a transformer is the ratio of the number of turns in the primary winding to the number of turns in the secondary winding. The *voltage ratio* is expressed as the ratio of the primary voltage to the secondary voltage. Figure 4-6 shows examples of these two ratios.

Occasionally, a transformer is referred to in terms of its *current ratio*. This is expressed as the ratio of the current in the primary to that in the secondary. Figure 4-6 gives a few examples of this ratio also.

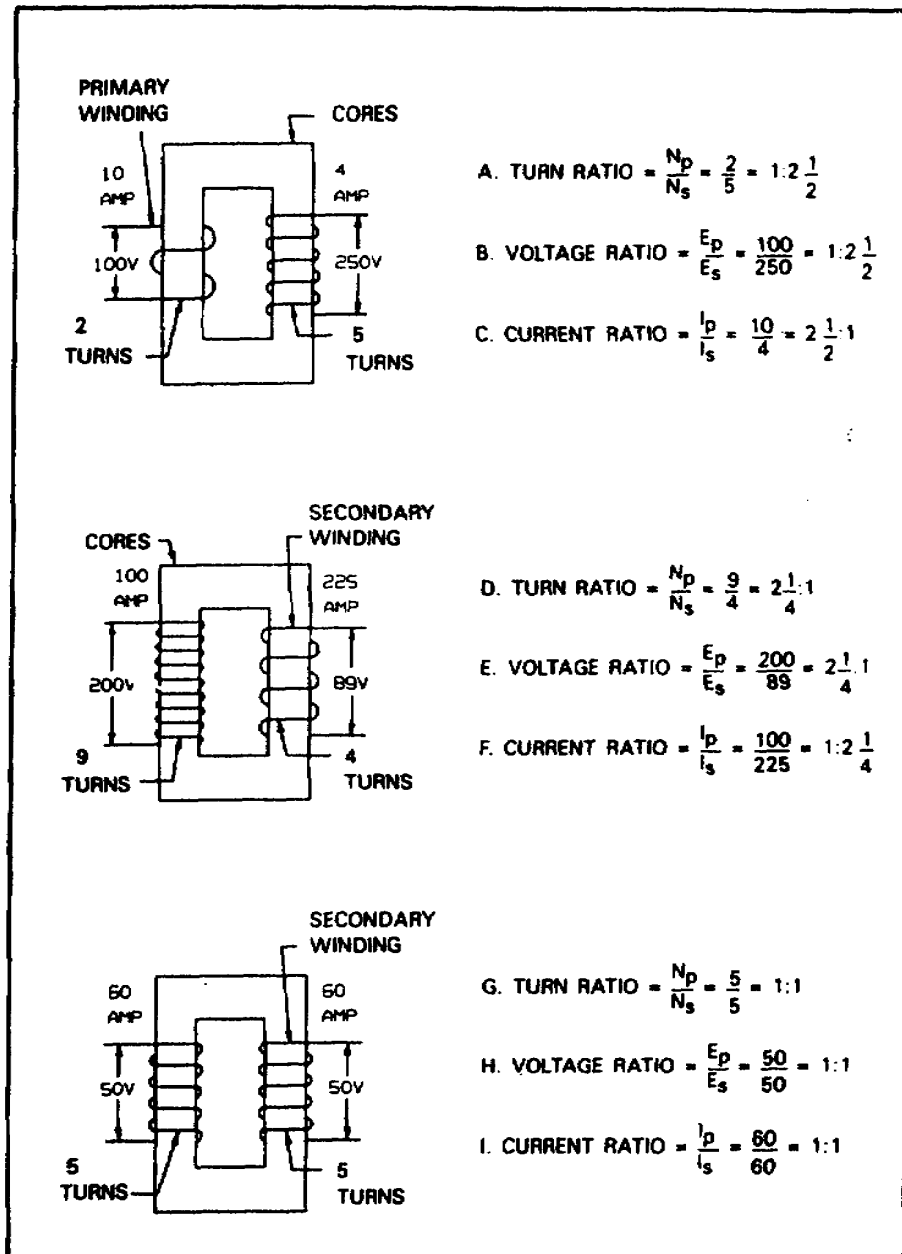


Figure 4-6. Transformer Ratio.

Phase Relationships

One of the uses of a transformer is getting a phase shift between circuits. You can use vectors to show how this is done.

The first consideration is that of a transformer with an open secondary (no load). Disregarding any resistance of the winding, the primary circuit contains only inductance. In figure 4-7A, using E_p as the base vector, I_p can be plotted lagging the applied voltage by 90° since the primary circuit is inductive.

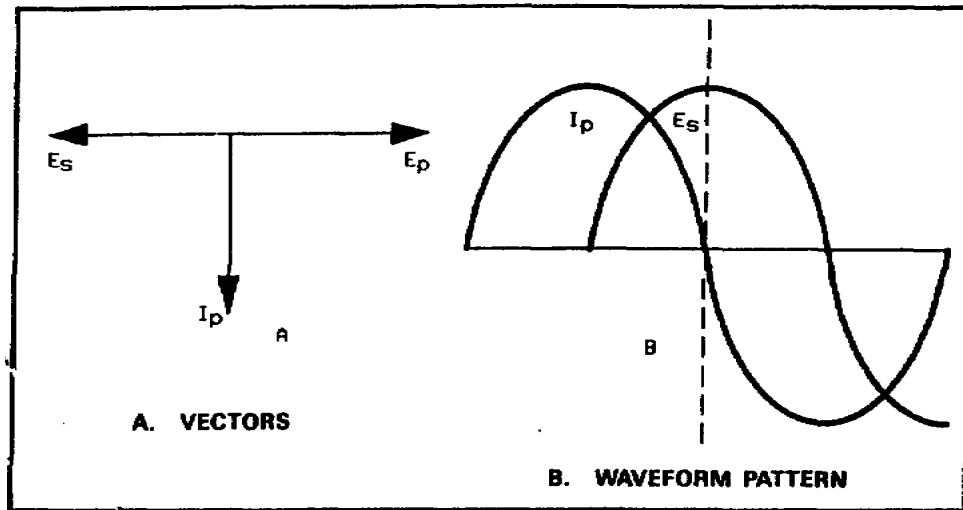


Figure 4-7. Phase Relationship Across a Transformer

Since the induced voltage is dependent upon the rate of change of flux, the rate of change is maximum when the primary current is passing through zero (figure 4-7B). This would indicate that, at that moment, the induced voltage would be maximum. The voltage induced in the secondary then lags I_p by 90° . The completed vector diagram shows that there is a 180° phase shift between the primary and secondary voltages. The vectors in figure 4-8 show the operation of a transformer with a resistive loaded secondary. In this case, the generator works into a resistive load. The current flowing in the secondary tends to magnetize the iron core in a direction opposite to the magnetizing action of the primary circuit. This causes a lower EMF in the primary. This decreases the opposition to current flow in the primary so that it approaches that of pure resistance. Therefore, E_p and I_p are practically in phase. Previously, you found that the induced voltage lags the primary current by 90° . If you picture the secondary winding as a generator, the voltage induced will be the source of voltage pressure that causes current to flow in the secondary. Therefore, consider the secondary circuit as a series resistive-inductive (RL) circuit. In actual transformers, the inductance values are quite large in comparison to the resistive loads, so you can say that the secondary current lags the induced voltage by approximately 90° . If you take the voltage from the secondary across the resistor, the current (I_s) and the voltage (E_s) are in phase. E_p and E_s are 180° out of phase.

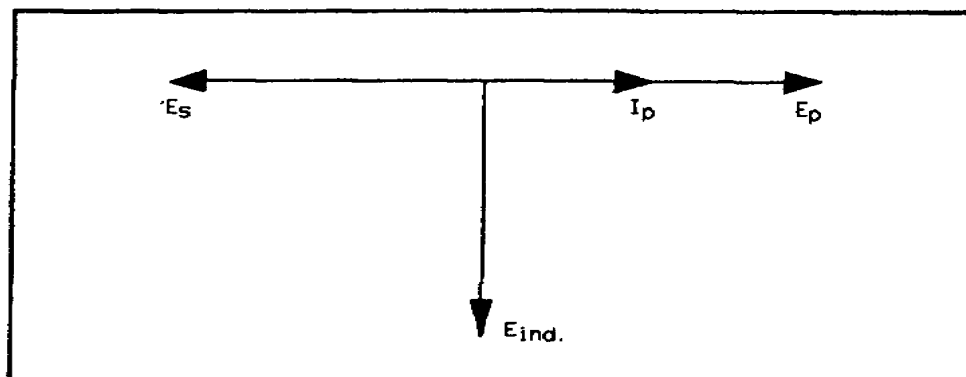


Figure 4-8. Vectors and Phase Relationship with Secondary Loaded

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Although in the two cases cited above there was a phase shift of 180° from primary to secondary, do not conclude that this will always be true. The degree of phase shift depends upon several factors: The type of load placed upon the secondary, the transformer's efficiency, and the manner in which the secondary is wound, with respect to the primary. In figure 4-9, the polarity of point C is 180° out of phase with point A. However, if point C were grounded instead of point D, the secondary voltage, with respect to ground, would be in phase with the primary voltage.

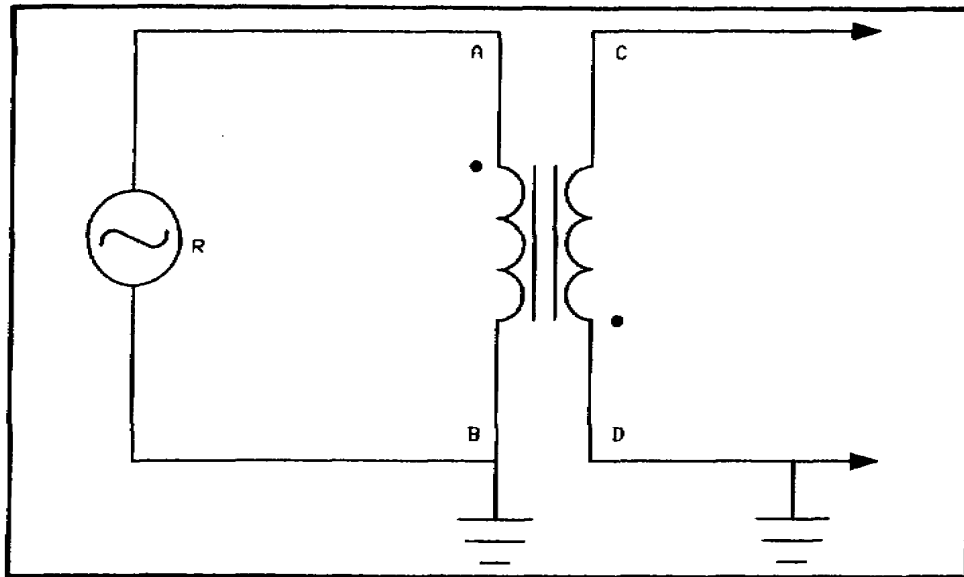


Figure 4-9. Phase Notation of a Transformer with Generator (R).

Mutual Inductance

In the discussion of coils you learned that a changing current through a coil induced a voltage in the coil which was in opposition to the applied voltage. This process is called self-induction. The ability of the coil to cause self-induction is inductance. In a transformer, a changing current through the primary induces a voltage in the secondary, and a changing current through the secondary induces a voltage in the primary. This is mutual induction.

Mutual inductance is a property of a transformer just like inductance is a property of a coil. As with inductance, the unit of inductance is the henry (h). The symbol of mutual inductance is the letter M. A transformer has a mutual inductance of one henry if a current change of one ampere per second in one coil induces one volt in the other coil.

The mutual inductance of a transformer is determined by its construction: the type of core, the number of turns in its coils, and its dimensions. Note that these factors also determine the inductance of coils. When all the lines of force set up by the primary cut all the turns of the secondary, and vice versa, M can be determined directly from the inductances of the primary and secondary (L_1 and L_2). In such a case, there is unity coupling.

$$M = \sqrt{L_1 L_2}$$

Coefficient of Coupling

The amount of coupling between the primary and secondary has a direct bearing on the mutual inductance. Coupling is indicated by the percentage of lines of force set by the primary that cut the secondary. If 80 percent of the lines set up by the primary cut the secondary, there is 80 percent coupling, or a coefficient of coupling of 0.8. Since mutual inductance is directly proportional to the coefficient of coupling, the general formula for mutual inductance is

$$M = K\sqrt{L_1 L_2},$$

where K is the coefficient of coupling.

Example:

What is the mutual inductance of a transformer whose primary has 16 h of inductance and whose secondary has 4 h, if the coupling between the two coils is 75 percent?

Solution:

$$M = K\sqrt{L_1 L_2}$$

$$M = 0.75\sqrt{16 \times 4}$$

$$M = 6 \text{ h}$$

The mutual inductance of the transformer is 6 h. From the study of inductance, you learned that if two coils (L_1 and L_2) were connected in series, the total inductance would be $L_t = L_1 + L_2$, providing there was no effect of coupling between the two coils. Since there usually is, the effect of coupling can be shown by an explanation of mutual inductance.

If the series coils are close enough, there will be the mutual inductance of the first coil on the second coil and also the mutual inductance effect of the second coil on the first. If the coils are connected in such a way that their fields add, they are said to be series aiding. In such a case, the total inductance is:

$$L_t = L_1 + L_2 + 2M.$$

To illustrate that formula, connect the transformer of the last example as shown in figure 4-10. L_1 in the problem was 16 h and L_2 was 4 h. The mu-

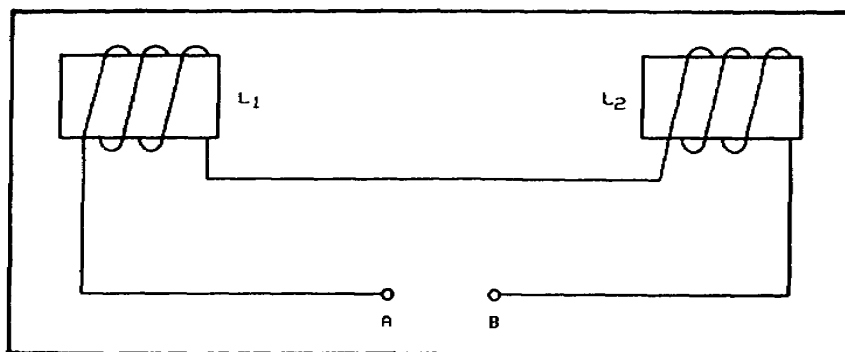


Figure 4-10. Series Aiding Mutual Inductance.

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tual inductance we solved for was found to be 6 h. The total inductance between A and B is:

$$L_t = L_1 + L_2 + 2M$$

$$L_t = 16 + 4 + (2 \times 6)$$

$$L_t = 32 \text{ h}$$

If you reverse the connections of one of the coils as shown in figure 4-11, the fields will have a canceling effect. The formula for total inductance in that case is:

$$L_t = L_1 + L_2 - 2M.$$

To the illustrative example, this would change our total inductance between A and B from 32 h to:

$$L_t = 16 + 4 - (2 \times 6)$$

$$L_t = 8 \text{ h.}$$

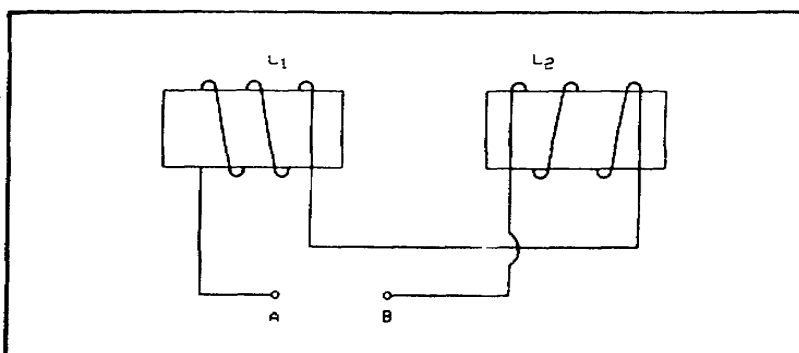


Figure 4-11. Canceling the Effect of Mutual Inductance.

Another factor affecting coupling is the angle at which the flux of one coil cuts that of another coil. If you pivot L_2 (figure 4-12) at the center, you will find that the M reduces to zero at 90° and actually subtract from the total

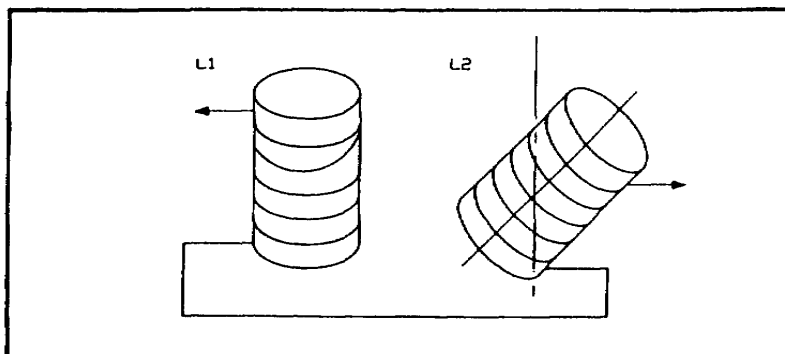


Figure 4-12. Angle Affect on Coupling.

inductance at between 90° and 270° . Note that at 180° or when the coils are directly opposing each other, the inductance is at a minimum. This is because the windings on L_1 and L_2 are in opposite directions (figure 4-13). For 90° rotation or 270° rotation, the total inductance is equal to $L_1 + L_2$. For 180° , it is $L_1 + L_2 - 2M$. For 0° and 360° , it is $L_t = L_1 + L_2 + 2M$.

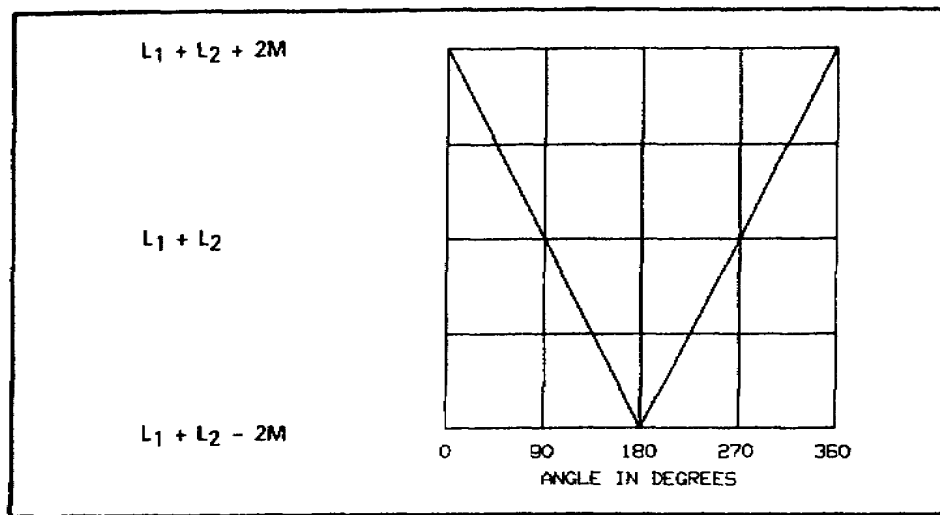


Figure 4-13. Plotted Angle Affect on Coupling.

Transformer Losses

Radar equipment is usually operated from special power units. Transformers are a vital part of these units. A transformer supplies the high voltage and current required for the operation of radar equipment.

To study a typical power transformer, you need a unit that gives you maximum transfer of energy from the primary to the secondary with minimum power loss and dissipation. In order to do this, the primary and secondary coils must be wound closely together for coupling. A core is inserted to direct the flux through the windings, thus minimizing flux leakage.

There are several factors to be taken into consideration in connection with the core of a transformer. Although you reduce flux leakage by providing a path for the magnetic lines of force, there are power losses in the transformer that must be minimized in order to obtain maximum efficiency.

There is a power loss in the primary due to the resistance of the windings. This is the normal I^2R loss. In addition, the resistance of the wire in the secondary gives I^2R loss in the secondary wiring. To keep the I^2R losses to a minimum, copper wire (as large as possible without making the transformer too bulky) is used.

There are other losses called iron losses. These are caused by the effects of primary and secondary currents in the core material (figure 4-14). The first of these losses is due to eddy-currents. When AC is applied to the windings, a voltage is induced in the core. This voltage sets up currents in the core that are more or less circular and that are called eddy-currents. Since the solid iron core has a large cross-sectional area and offers very little resistance, large values of eddy-currents flow and produce heat.

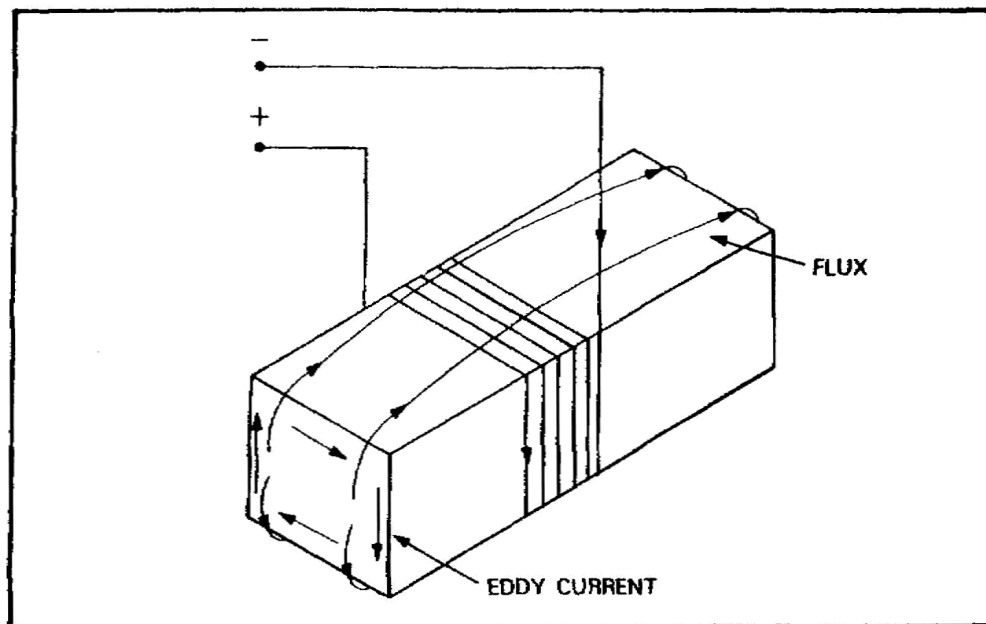


Figure 4-14. Section of Solid Iron Core.

This eddy-loss problem is overcome by using thin sheets of core material called laminations (figure 4-15). These are either varnished or have their surfaces treated to provide insulation. When several of these thin sheets are placed together, there is no electrical contact between them. A complete transformer core is many of these thin laminations stacked together providing a large core area and increased electrical resistance to the eddy-currents. There is now a satisfactory core area with a minimum amount of eddy-current losses.

The second type of iron loss is hysteresis. Hysteresis in an iron core means that the magnetic flux or lines of force lag behind the magnetizing force that causes them. Recall the phenomena from the study of magnetism. The friction caused by the little molecular magnets heat up as they try to align themselves with the constantly changing direction of the current flow in the primary. This heat is wasted energy. Let us briefly review our study of magnetism in order to get a clearer picture of hysteresis.

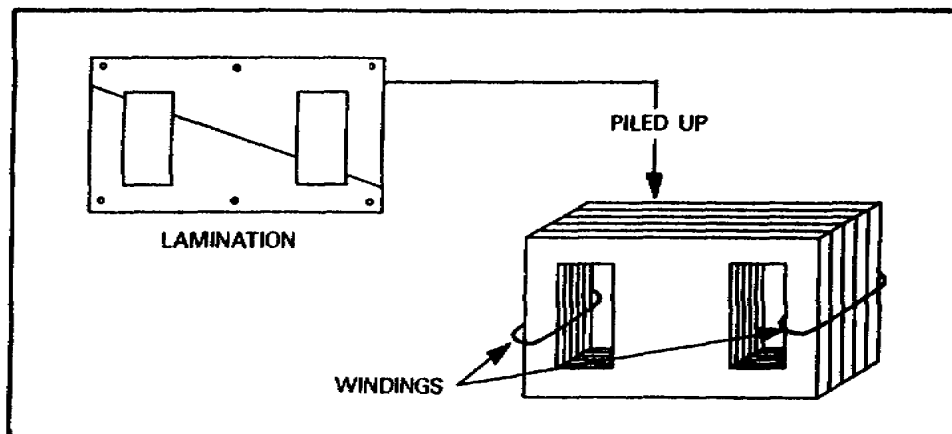


Figure 4-15. Laminated Iron Core.

Curve B of figure 4-16 represents the flux density changes in relation to the magnetomotive changes (curve H). Note that both the H and B curves start out from T_0 and continue toward T_1 in phase. When curve H reaches T_1 , it is at its maximum value in the positive direction and begins to decrease toward T_2 , to complete the half cycle. Now, note curve B. It does not reach the zero line until sometime later. The actual time distance is represented by space Y. To complete the cycle, you can see that the H curve reaches zero before the B curve by a time equivalent to space Z.

When the core of the transformer is magnetized, the atoms of the core material will be aligned in one direction. As the magnetizing force decreases to zero at T_2 (figure 4-16), the magnetizing action of the AC leaves the atoms of the core lined up for a period of time corresponding to space Y. This is what causes the flux to lag behind the magnetomotive force. The magnetism left in the core material after H has reduced to zero is called residual magnetism. When AC is used to magnetize the core, whatever residual magnetism placed in the core in one-half cycle is overcome in the next half cycle because of the reversal of polarity.

At points Y and Z in figure 4-16, where residual magnetism is present, it requires energy from the magnetomotive force to overcome it. This energy is dissipated as heat in the core. This waste of energy is the hysteresis loss and must be kept to a minimum for efficient operation.

The losses due to hysteresis and eddy-currents, iron losses along with I^2R (copper) losses make up all the transformer losses. Due to these losses, the transformer cannot be 100-percent efficient. Therefore, the power taken from the secondary can never equal the power applied to the primary. You can find efficiency of a transformer from the following equation:

$$\text{Efficiency percentage} = \frac{P_s}{P_p} \times 100\%,$$

where P_s is total power in the secondary, and P_p is total power in the primary

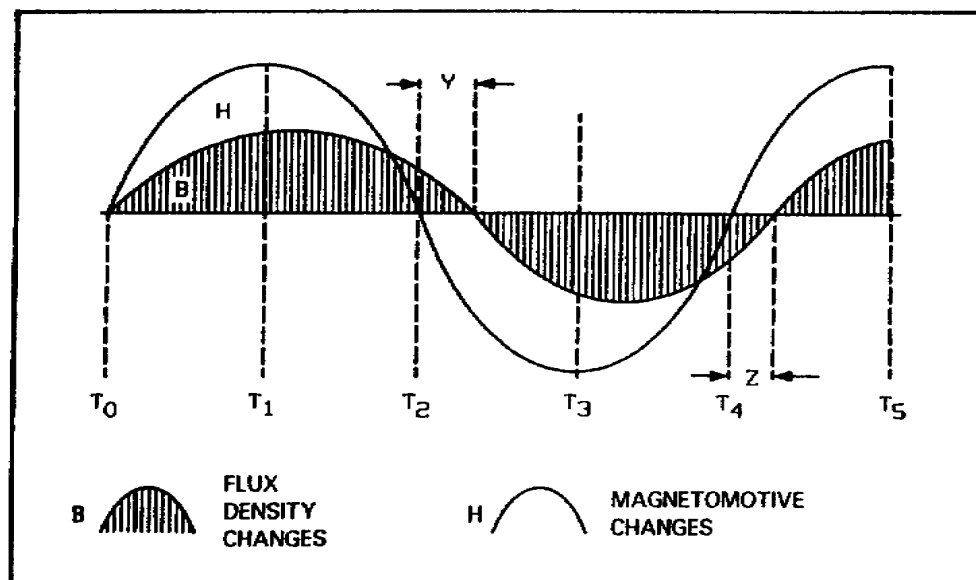


Figure 4-16. Flux Density and Magnetomotive Force.

POWER TRANSFORMERS

In power transformers, you can usually distinguish between the high and low voltage windings by the relative diameter of the wire. The low voltage side has the higher current; therefore, it has the larger diameter wire. You can use ohmmeter resistance check to identify windings for sure.

A typical power transformer has color-coded leads so that it is easy to pick out the primary and secondary windings. Figure 4-17 shows the numbered and colored leads for the transformer. Figure 4-18 in the schematic is for that transformer. The black leads are the primary; the red leads are the high-voltage secondary winding; and the red and orange lead is the center-tap. The yellow indicates the 5-V secondary; green indicates the 6.3-V secondary; and green and yellow is the center-tap. If the leads are not color-coded, they will be numbered on the transformer. Those numbers will be found in schematics of the equipment.

There are several types of power transformers, from the huge transformer installed in the commercial powerhouses to the small ones used with radar equipment. Transformers used in radar have a sufficiently low degree of loss to permit the heat generated to be radiated naturally from the surfaces of the coils and core without exceeding the safe operating temperature. This class of transformer is called the dry, self-cooling type.

With high-power transformers, the external surfaces of the core and coils are not sufficient to dissipate the heat by natural radiation and convection. These units are immersed in a tank of oil. The oil conducts the heat from the core and coil by convection to the surface of the tank wall, where it is dissipated by radiation. This type of transformer is also in radar equipment.

So far, the power transformers discussed have had only one secondary winding. More often there are several secondary windings, each providing a different voltage. Look at figure 4-18; it is a schematic of a typical power transformer used in electronic circuits.

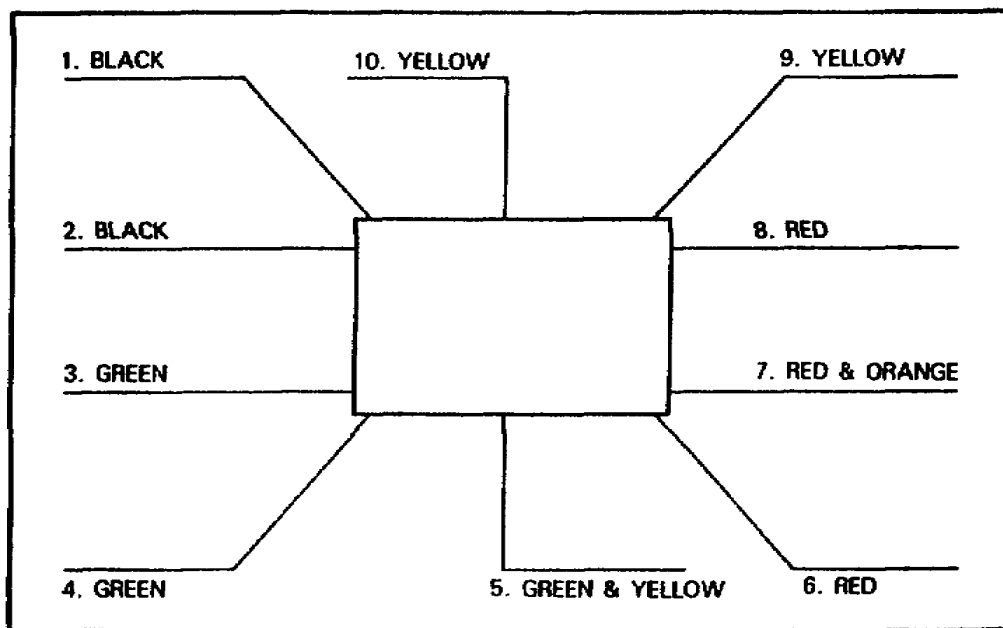


Figure 4-17. Number and Color Coded Power Transformer.

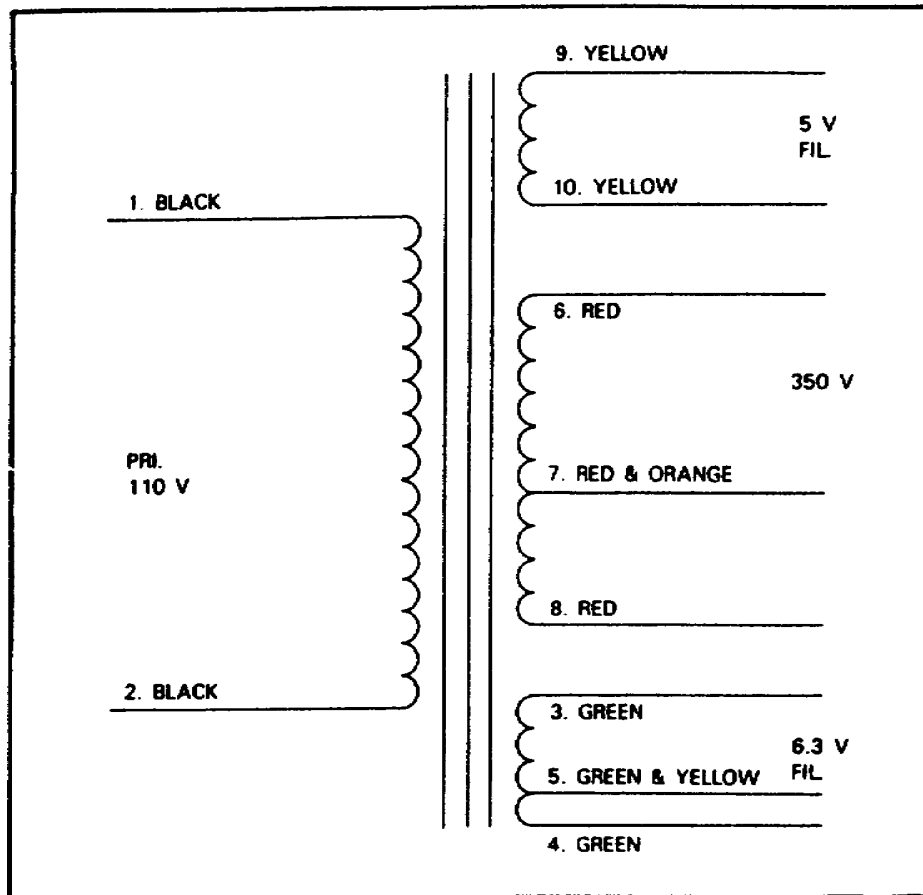


Figure 4-18. Typical Power Transformer Schematic.

Another type of power transformer is the autotransformer. It is called an autotransformer because the primary and secondary windings are actually incorporated as one winding. Figure 4-19 is an autotransformer with a movable tap in the secondary which enables selection of desired voltage values.

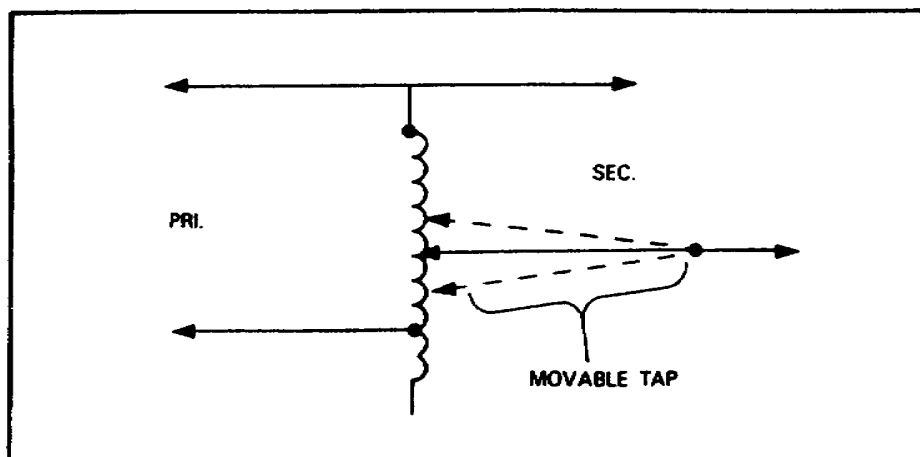


Figure 4-19. Autotransformer.

AUDIO TRANSFORMERS

As yet the effect of frequency on a transformer has not been considered. The rapidly changing polarity of voltage at frequencies higher than normal power frequencies increases the iron losses due to residual magnetism. This is evident since the molecular friction, due to the rapidly changing polarity, is increased as the frequency increases.

For transferring energy from one circuit to another at audio frequencies, special transformers use a core material having a very low degree of retention. At these higher frequencies, residual magnetism left in the core material by the effect of one-half cycle will cause an undesirable lag in the secondary voltage. Audio frequencies range. Because audio transformers must transfer this range of frequencies from about 20 to 20,000 Hz from one circuit to another without distortion, they are very carefully designed. In some cases, the secondary is center tapped, and when it is, great care is taken to see that the windings contain the same inductance on each side of the center tap.

RADIO FREQUENCY TRANSFORMERS

When working with the radio frequencies (RF) (above the audio range), the iron core transformer used for power and audio frequencies is no longer practical. The advantage from reducing flux leakage through the use of a suitable core is offset by the loss due to hysteresis at these frequencies. Many RF transformers have air cores. Some, however, use special powdered iron cores.

Air core transformers have very little coupling between the primary and secondary, since all the flux emanating from the primary is not cutting the secondary winding.

You can assume that the coefficient of coupling is so small it is negligible in regard to the effect of secondary load on the primary circuit. Vectorially, you can show an air core transformer (figure 4-20) with an unloaded secondary the same way you plotted the iron core transformer. For practical application, however, the secondary of the air core transformer is usually loaded with a capacitor

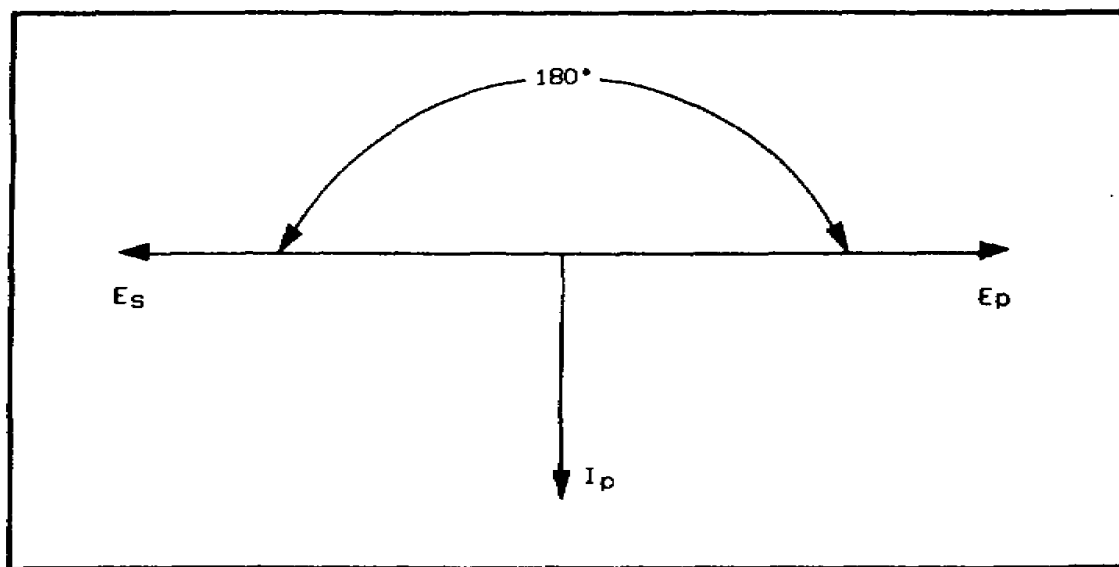


Figure 4-20. Vector Diagram of an Air Core Transformer.

In figure 4-21, the secondary circuit is an LC circuit. You know that L and C is resonant at some frequency determined by the values of L and C. The secondary winding can be considered a generator. This being the case, the secondary is actually a series LC circuit. You can assume that the secondary circuit has negligible effect on the primary circuit.

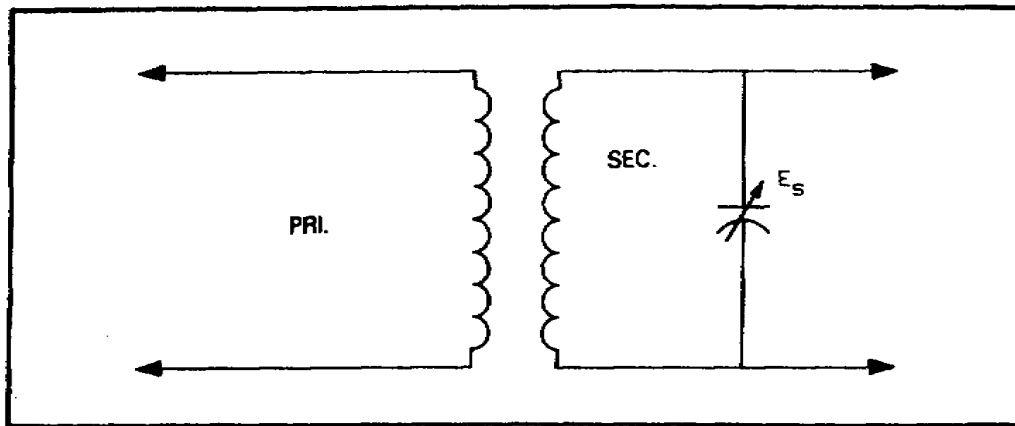


Figure 4-21. Air Core Transformer.

You can see that the primary is a simple inductive circuit in which the current lags the voltage by 90° . This is shown in figure 4-22. You also know that the induced voltage (E_{ind}) lags I_p by 90° . To determine lag in the secondary, first assume that the secondary circuit is tuned to resonate at the frequency of the applied voltage. At resonance, the two reactances cancel leaving only the resistance of the circuit. Therefore, the secondary current is in phase with the induced voltage. However, secondary voltage is being obtained across the capacitor; this voltage lags the current by 90° . The result is that the secondary voltage (E_c) leads the primary voltage by 90° .

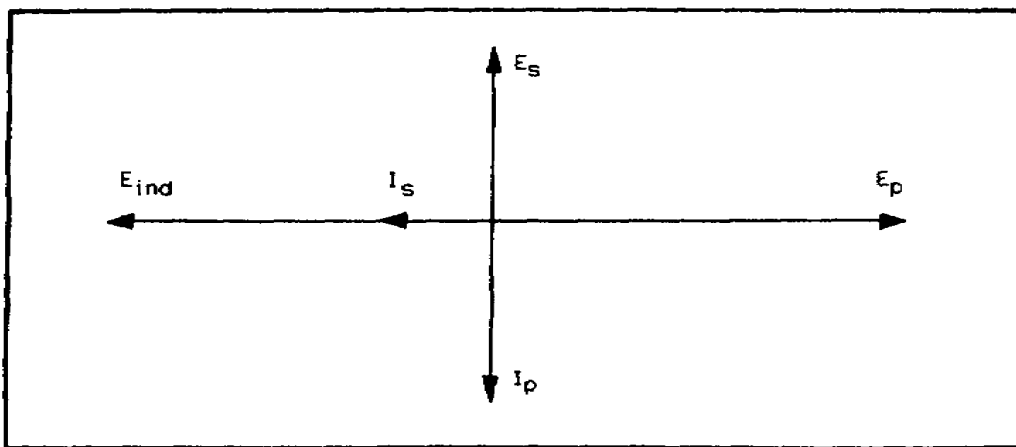


Figure 4-22. Vector Diagram for a Tuned Secondary

By leaving the secondary tuned to the same frequency, you can determine what to expect if higher frequency is applied to the primary (figure 4-23). The E_p , I_p , and E_{ind} vectors are the same. In the secondary however, since the frequency is higher than the resonant frequency, the circuit acts inductively. This being the case, as you deviate from the resonance, the I_s lags the

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E_{ind} until a frequency is reached at which the circuit becomes predominately inductive. At this time, I_s lags E_{ind} about 90° . Again, there is an output across the capacitor, and the voltage lags the secondary current by 90° . Note that the secondary voltage is almost in phase with the primary voltage in this case.

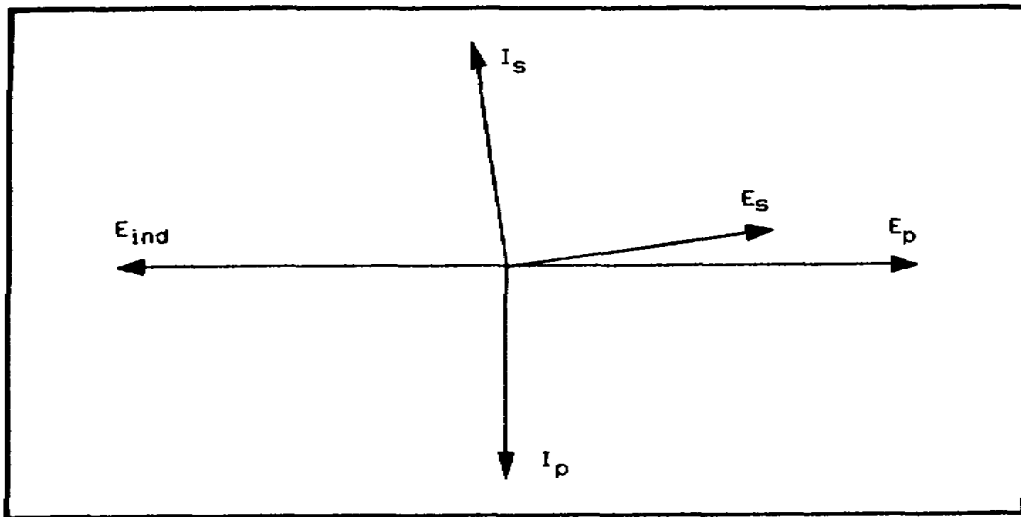


Figure 4-23. Vector Diagram of Applied Frequency Higher than Tuned Frequency.

At a frequency below the resonant frequency, the resultant vector would appear as in figure 4-24. The secondary, in this case, would act capacitively, and the current would be leading E_{ind} by almost 90° by the time the frequency was decreased to a point where the circuit would be predominately capacitive. In this case, the secondary voltage is approximately 180° out of phase with the primary voltage.

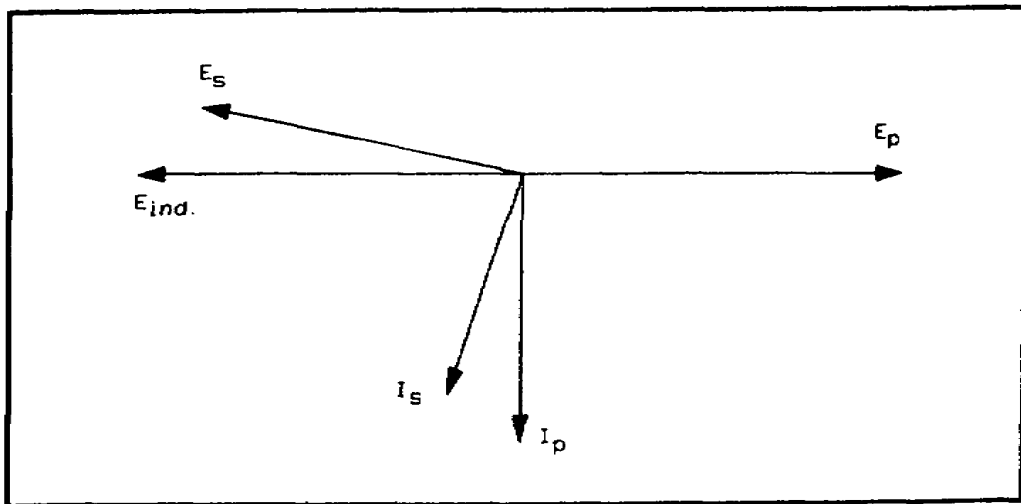


Figure 4-24. Vector Diagram of Applied Frequency Higher than Tuned Frequency.

By changing the inductance or capacitance in the secondary (frequency in this case being constant), the degree of phase shift between the primary and secondary voltages can be varied anywhere from practically 0° to nearly 180° .

There is another type of RF transformer in which a higher coefficient of coupling is desired. To get it, a powdered iron core is inserted in the windings. This core is nothing more than small particles of iron suspended in a plastic material so that they are insulated from each other. Although there is no complete magnetic path for this flux, this type of core does offer a higher degree of coupling than air. Usually these cores can be adjusted, in and out of the windings, to produce a variable inductance.

SATURABLE TRANSFORMERS

In your study of magnetization curves, you noted that, if the magnetizing force is increased enough, a point known as saturation would be reached. The ordinary power transformer is operated well below saturation. However, there are special circuits in which magnetic saturation is used. A transformer used in a circuit where saturation is desired is called a saturable transformer.

After the point of magnetic saturation is reached, the flux density is practically constant even though the force causing the flux is increased. Also, a stationary flux cannot induce a voltage. With these facts in mind, the operation of a saturable transformer will be easy to understand.

In the unsaturated transformer, the current in the primary lags the voltage across the primary by 90° . Figure 4-25 shows this phase relationship between E_p and I_p . Also, the value of current will depend upon the magnitude of the applied voltage.

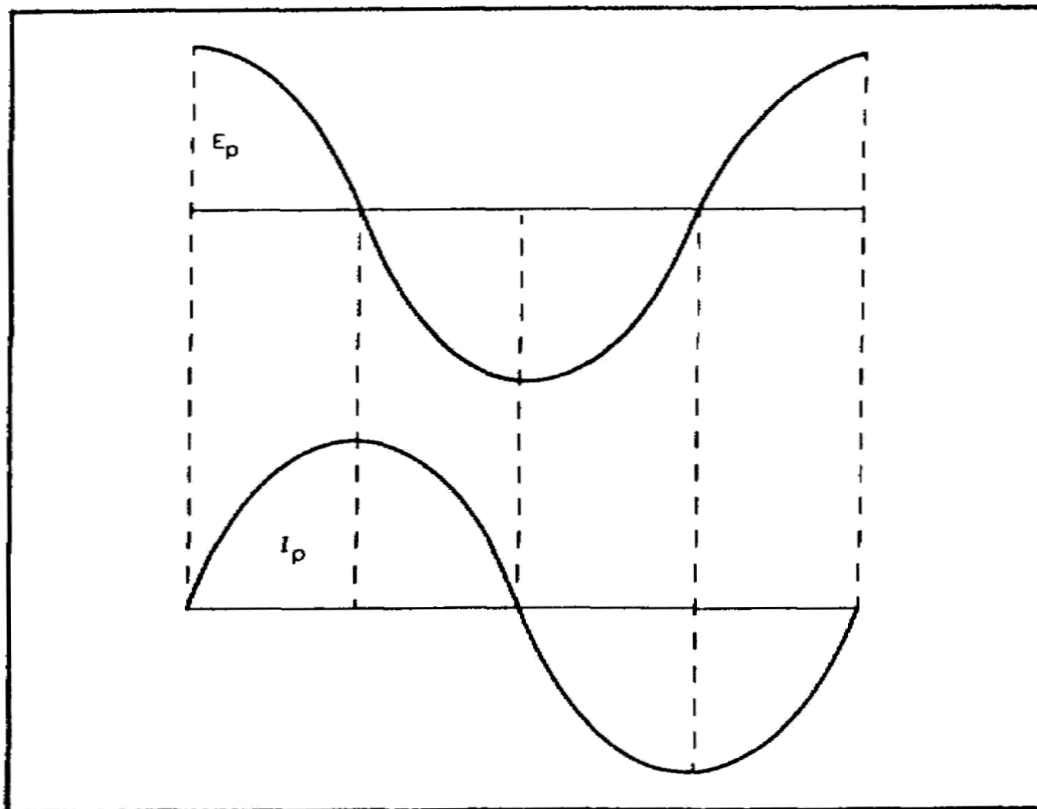


Figure 4-25. Phase Relationship Between Current and Voltage on the Primary of an Unsaturated Transformer.

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To explain the action of saturable transformers, assume there is no load on the secondary. Also, assume the applied voltage is a higher value than that needed to cause enough current to flow to saturate the core. Figure 4-26 is a graph of this transformer's operation. At time T_0 , I_p is at zero and E_s is at a maximum negative value, since it lags I_p by 90° . As the primary current starts to build up in a positive direction, E_s starts to decrease toward zero. At time T_1 on the I_p curve, the current has reached a value where the core is magnetically saturated. Any further increase in I_p does not affect the flux, and no voltage is induced in the secondary. At time T_1 , E_s therefore drops to zero. Since the core is saturated, the inductive reactance of the primary will not prevent I_p from reaching a high value. The dotted line on the I_p curve represents the normal current flow without saturation.

As long as I_p remains at a value higher than that necessary to saturate the core, the flux produced will remain at a constant level, and no voltage will be induced in the secondary. This action is shown from T_1 to T_2 . At time T_2 , I_p has reached the value necessary to saturate the core and is decreased below that point. Since the flux is again changing, a voltage is induced in the secondary and E_s rises to its positive maximum value at T_3 . Toward T_4 , I_p is increasing in amplitude in the negative direction and, at T_4 , again produces magnetic saturation in the core. With the flux again stationary E_s

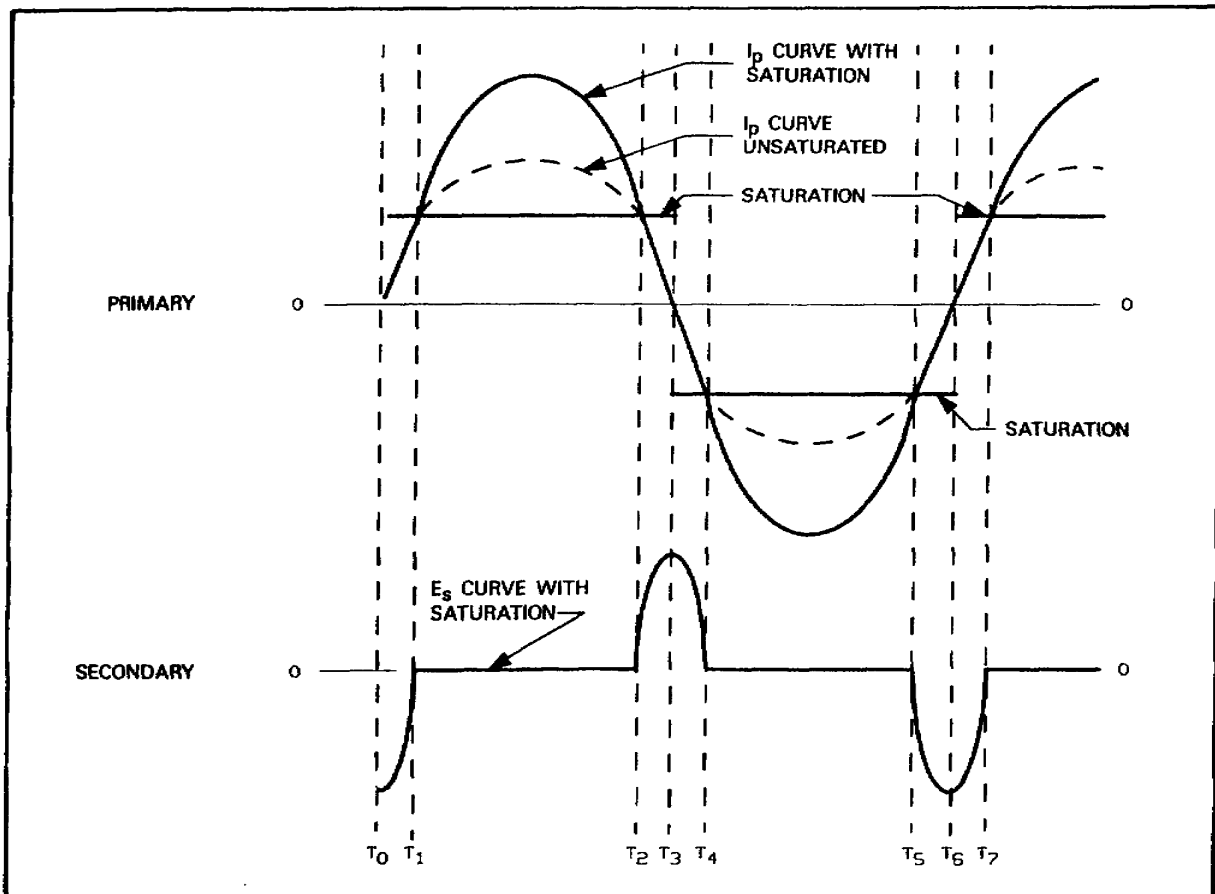


Figure 4-26. Output Waveshape of a Saturable Transformer.

drops to zero at T_4 . E_s remains at zero until time T_5 when I_p again falls below the value required to produce saturation. As I_p passes through zero on its positive swing, E_s reaches its negative maximum peak and the action at T_6 is identical to that at point T_0 .

From the secondary, voltage pulses will be obtained rather than the normal sine wave of voltage. See figure 4-26.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What will happen if the primary current in a transformer remains at some steady finite value?
 - a. The primary field will collapse.
 - b. The secondary field will collapse.
 - c. The secondary induced voltage will increase to maximum.
 - d. The secondary current remains at a steady finite value.
2. What is the normal phase difference, in $^{\circ}$, between the primary and secondary voltages in a transformer?
 - a. 180.
 - b. 120.
 - c. 90.
 - d. 60.
3. What is the induced secondary input, in volts, of this circuit? See figure 4-27.
 - a. 50
 - b. 100.
 - c. 200.
 - d. 400.
4. How much current, in amps, is flowing in the secondary circuit? See figure 4-27.
 - a. 0.
 - b. 2.5.
 - c. 5.
 - d. 10.
5. What is the power, in watts, in the secondary? See figure 4-27.
 - a. 1,000.
 - b. 500.
 - c. 200.
 - d. 100.

6. What BEST describes the turns ratio of this transformer circuit? See figure 4-27.
- 1 to 2 step-up.
 - 1 to 2 step-down.
 - 3 to 1 step-down.
 - 3 to 1 step-up.
7. What is the impedance, in ohms, of the secondary of a step-down transformer that has a turns ratio of 2:1 and a primary impedance of 2,000 Ω ? See figure 4-27.
- 8,000.
 - 5,000.
 - 1,000.
 - 500.
8. If the current ratio of a transformer is 4:1, what is the turns ratio? See figure 4-27.
- 1 turn in primary for every 4 in secondary.
 - 4 turns in primary for every 1 in secondary.
 - 2 turns in primary for every 1 in secondary.
 - 1 turn in primary for every 2 in secondary.

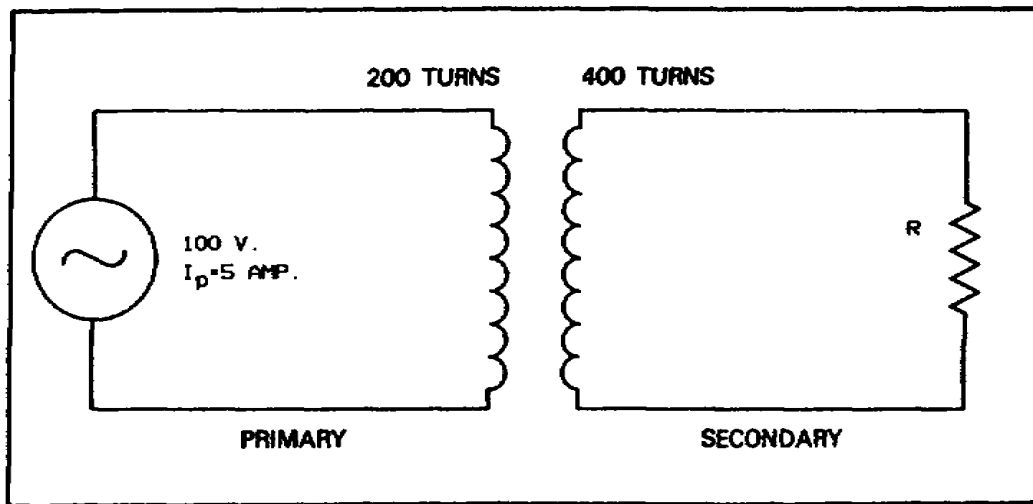


Figure 4-27. Transformer (Unity Coupling).

9. What is the transformer coefficient of coupling, if the primary inductance is 9 h, the secondary inductance is 4 h, and the mutual inductance is 4 h?
- .80.
 - .75.
 - .66.
 - .52.

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10. What currents in a transformer core follow a circular path?
 - a. Eddy
 - b. Primary.
 - c. Secondary.
 - d. Tertiary
11. Why are laminated cores used in transformers?
 - a. To increase power losses.
 - b. To increase voltage turns ratio.
 - c. To increase current turns ratio.
 - d. To reduce power losses.
12. What form of magnetism remains in a transformer's core after the magnetizing current becomes zero?
 - a. Initial.
 - b. Positive.
 - c. Negative.
 - d. Residual.
13. How are the low and high voltage sides of a power transformer identified?
 - a. Low voltage side has larger wire diameter.
 - b. High voltage side has larger wire diameter.
 - c. High voltage side is colored black.
 - d. Low voltage side is colored black
14. Why are high power transformers immersed in oil?
 - a. To decrease heat dissipation.
 - b. To increase heat dissipation.
 - c. To decrease coupling
 - d. To increase coupling.
15. What is the characteristic of the winding of an autotransformer?
 - a. Parallel primary and secondary.
 - b. Series primary and secondary
 - c. One winding for primary and secondary.
 - d. Two windings for primary and secondary.

16. What range of frequencies is transferred by audio transformers?
- a. 25 kHz to 60 kHz.
 - b. 25 kHz to 50 kHz.
 - c. 20 kHz to 30 kHz.
 - d. 20 Hz to 20 kHz.
17. What type of circuit is employed in figure 4-28?
- a. Tuned secondary.
 - b. Tuned primary.
 - c. Step-up.
 - d. Step-down.
18. How can the coupling in the circuit be increased? See figure 4-28.
- a. By decreasing the mutual inductance.
 - b. By increasing C.
 - c. By decreasing C.
 - d. By inserting a powdered iron core.

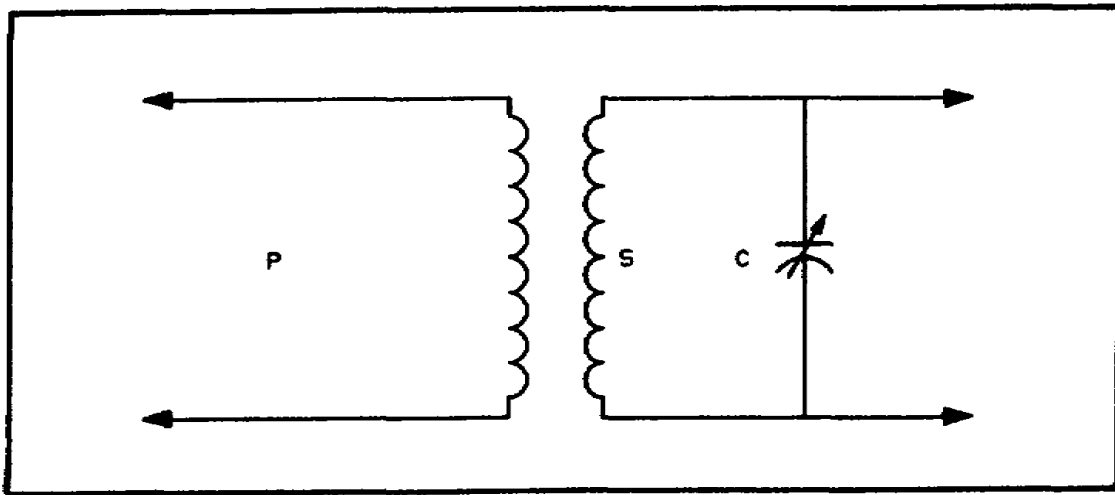


Figure 4-28. Tuned Transformer.

19. What condition indicates transformer saturation?
- a. Flux increased by magnetizing force increase.
 - b. Flux remains constant even though magnetizing force decreases.
 - c. Flux decreased by magnetizing force increase.
 - d. Flux remains constant even though magnetizing force increases.

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20. What characterizes an ideal transformer?
- a. The primary voltage equals secondary voltage.
 - b. The primary power exceeds secondary power.
 - c. The primary power equals secondary power.
 - d. The primary current equals secondary current.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed two or more questions, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

EXERCISE SOLUTIONS**Lesson 1**

1. d (see page 7).
2. c (see page 8).
3. b (see page 8).
4. c (see page 11).
5. c (see page 12).
6. b (see page 12).
7. a (see page 10).
8. c (see page 13).
9. c (see page 32).
10. b (see page 11).
11. b (see page 12).
12. a (see page 16).
13. d (see page 19).
14. c (see pages 19, 20).
15. d (see page 26).
16. b (see page 32).
17. a (see page 20).
18. c (see page 29).
19. b (see page 17).
20. a (see page 32).

Lesson 2

1. c (see page 40).
2. c (see page 41).
3. a (see page 42).
4. d (see page 42).
5. c (see page 46).
6. b (see page 48).
7. a (see page 49).
8. a (see page 50).
9. d (see page 49).
10. b (see page 52).

11. d (see page 47).
12. b (see page 49).
13. a (see page 41).
14. b (see page 42).

Lesson 3

1. b (see page 56).
2. a (see page 58).
3. c (see page 58).
4. d (see page 58).
5. b (see page 59).
6. a (see page 61).
7. d (see page 61).
8. b (see page 63).
9. d (see page 63).
10. a (see page 63).
11. a (see page 71).
12. d (see page 70).
13. c (see page 71).
14. d (see page 72).
15. a (see page 71).

Lesson 4

1. b (see page 78).
2. a (see page 85).
3. c (see page 80).
4. b (see page 81).
5. b (see page 81).
6. a (see page 83).
7. d (see pages 82, 83).
8. a (see pages 79, 80, 83).
9. c (see page 87).
10. a (see page 89).

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|----------------------|----------------------|
| 11. d (see page 90). | 16. d (see page 94). |
| 12. d (see page 91). | 17. a (see page 95). |
| 13. a (see page 92). | 18. d (see page 97). |
| 14. b (see page 92). | 19. d (see page 97). |
| 15. c (see page 93). | 20. c (see page 81). |