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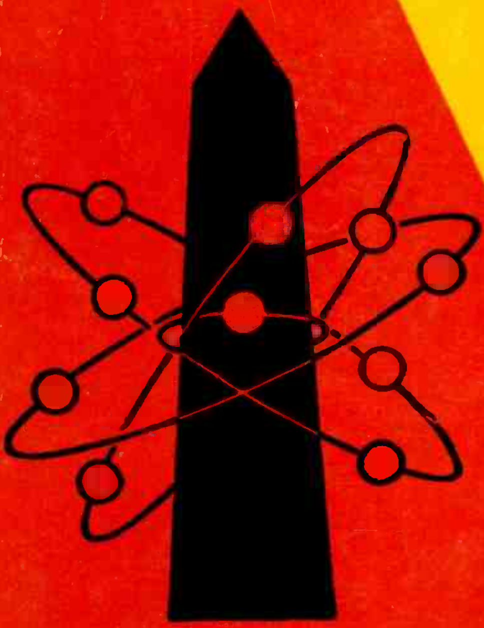
basic electricity

by VAN VALKENBURGH, NOOGER & NEVILLE, INC.



VOL. 4

IMPEDANCE

ALTERNATING CURRENT CIRCUITS

SERIES AND PARALLEL RESONANCE

TRANSFORMERS

A. STICH

RIDER

basic electricity

by VAN VALKENBURGH,
NOOGER & NEVILLE, INC.

VOL. 4

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PREFACE

The texts of the entire Basic Electricity and Basic Electronics courses, as currently taught at Navy specialty schools, have now been released by the Navy for civilian use. This educational program has been an unqualified success. Since April, 1953, when it was first installed, over 25,000 Navy trainees have benefited by this instruction and the results have been outstanding.

The unique simplification of an ordinarily complex subject, the exceptional clarity of illustrations and text, and the plan of presenting one basic concept at a time, without involving complicated mathematics, all combine in making this course a better and quicker way to teach and learn basic electricity and electronics. The Basic Electronics portion of this course will be available as a separate series of volumes.

In releasing this material to the general public, the Navy hopes to provide the means for creating a nation-wide pool of pre-trained technicians, upon whom the Armed Forces could call in time of national emergency, without the need for precious weeks and months of schooling.

Perhaps of greater importance is the Navy's hope that through the release of this course, a direct contribution will be made toward increasing the technical knowledge of men and women throughout the country, as a step in making and keeping America strong.

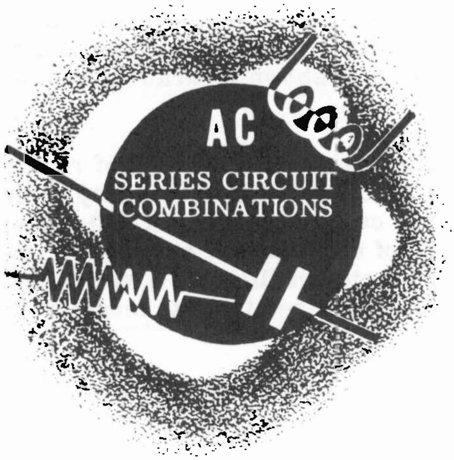
Van Valkenburgh, Nooger and Neville, Inc.

New York, N. Y.
October, 1954

TABLE OF CONTENTS

VOL. 4 — BASIC ELECTRICITY

AC Series Circuit Combinations



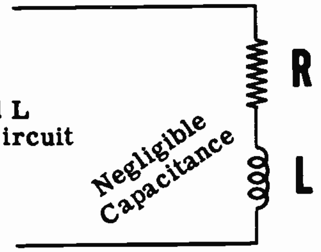
Various combinations of R, L and C may be used to form AC series circuits. If two factors are negligible, the circuit may consist of only R, only L or only C. However if only one factor is negligible, as is the case in many AC series circuits, it may consist of R and L, R and C, or L and C. If no factors are negligible the circuit consists of R, L and C, and all three factors will affect the current flow.

R + C in series is impedance

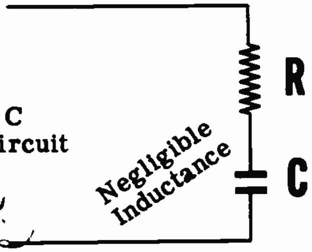
You have found out how R, L and C individually affect AC current flow, phase angle and power in AC circuits containing only one of these factors. Now you will find out how the various combinations of R, L and C affect AC series circuits consisting of any two, or of all three, of these factors.

Every electric circuit contains a certain amount of resistance (R), inductance (L) and capacitance (C). Inductance and capacitance cause inductive and capacitive reactance (X_L and X_C), which oppose the flow of AC current in a circuit, so that AC circuits contain three factors which oppose current flow: R, X_L and X_C. For a given circuit any of these factors may be so negligible that it can be disregarded.

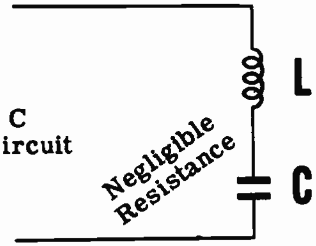
R and L
Series Circuit



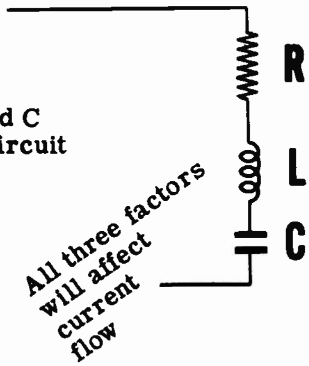
R and C
Series Circuit



L and C
Series Circuit



R, L and C
Series Circuit



IMPEDANCE IN AC SERIES CIRCUITS

R and L Series Circuit Impedance

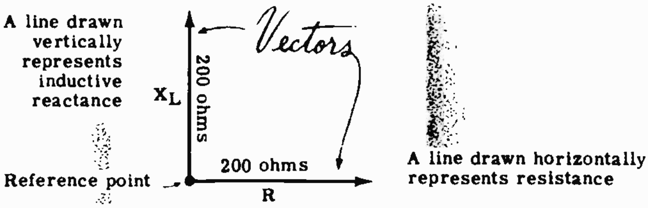
When resistance and inductance are connected in series, the total opposition is not found by adding these two values directly. Inductive reactance causes current to lag the voltage by 90 degrees, while for pure resistance the voltage and current are in phase. Thus the effect of inductive reactance as opposed to the effect of resistance is shown by drawing the two values at right angles to one another.

For example, suppose your series circuit consists of 200 ohms of resistance in series with 200 ohms of inductive reactance at the frequency of the AC voltage source. The total opposition to current flow is not 400 ohms; it is approximately 283 ohms. This value of total opposition, called "impedance," is obtained by a method called "vector addition." A vector is a straight line with an arrow at one end depicting direction, the length of the line depicting magnitude.

To add 200 ohms of resistance and 200 ohms of inductive reactance, a horizontal line is drawn to represent the 200 ohms of resistance. The end of this line, which is to the left, is the reference point, and the right end of the line is marked with an arrow to indicate its direction. To represent the inductive reactance, a vertical line is drawn upward from the reference point. Since X_L and R are each 200 ohms, the horizontal and vertical lines are equal in length. These lines are called "vectors."

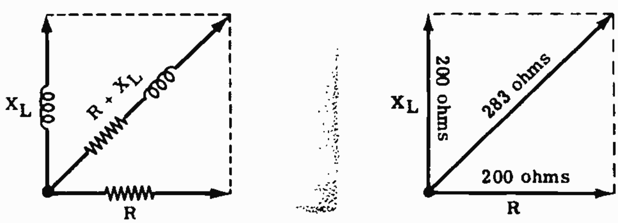
In a series circuit the resistance vector is usually drawn horizontally and used as a reference for other vectors in the same diagram.

REPRESENTING R AND X_L AS VECTORS



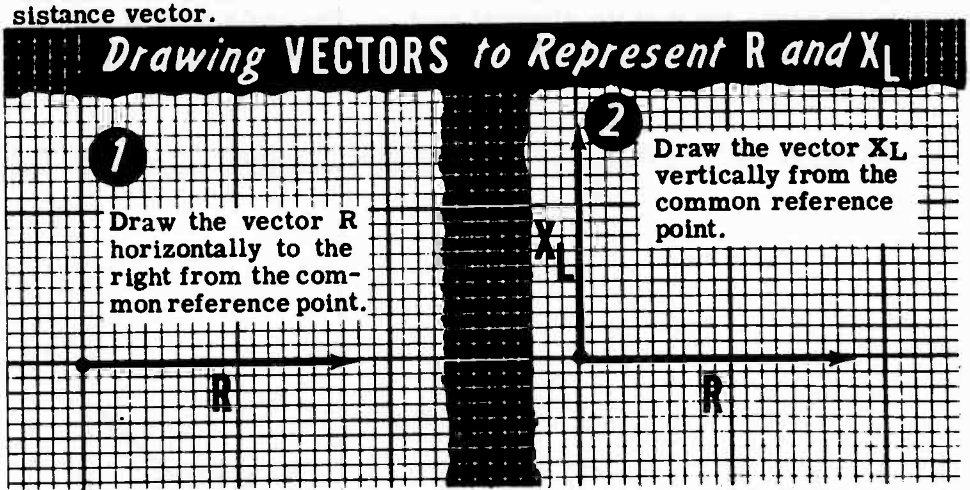
A parallelogram is completed as shown. The diagonal of this parallelogram represents the impedance Z, the total opposition to current flow of the R and L combination. Using the same scale of measure, this value is found to be 283 ohms at a phase angle of 45 degrees.

COMBINING VECTORS R AND X_L TO FIND THE IMPEDANCE

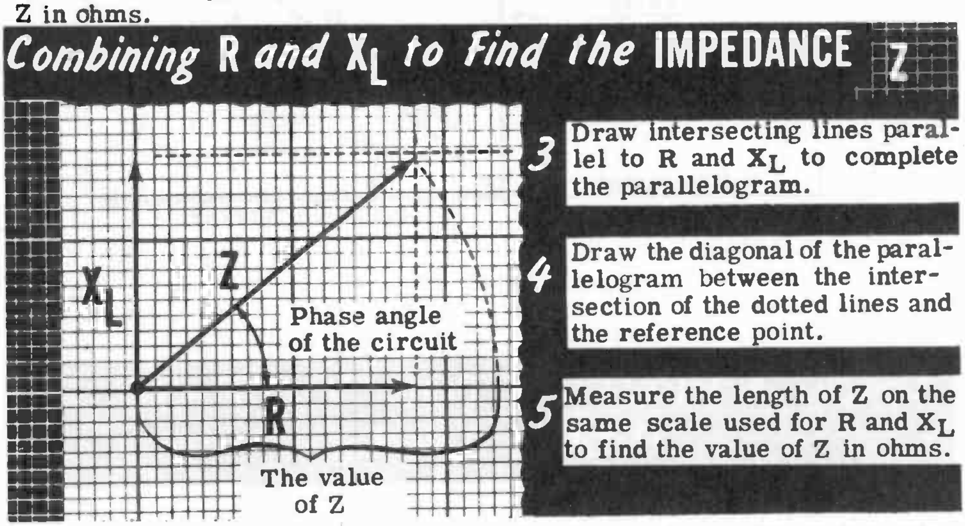


R and L Series Circuit Impedance (continued)

If the resistance and inductance values of a series circuit containing R and L are known, the impedance can be found by means of vectors. First, the inductive reactance X_L is computed by using the formula $X_L = 2\pi fL$ to obtain the value of X_L in ohms. Then the vectors representing R and X_L are drawn to scale on graph paper. A common reference point is used with the resistance vector R drawn horizontally to the right, and the inductive reactance vector X_L drawn upward, perpendicular to the resistance vector.



Next the parallelogram is completed, using dotted lines, and the diagonal is drawn between the reference point and the intersection of the dotted lines. The length of the diagonal represents the value of the impedance Z in ohms.



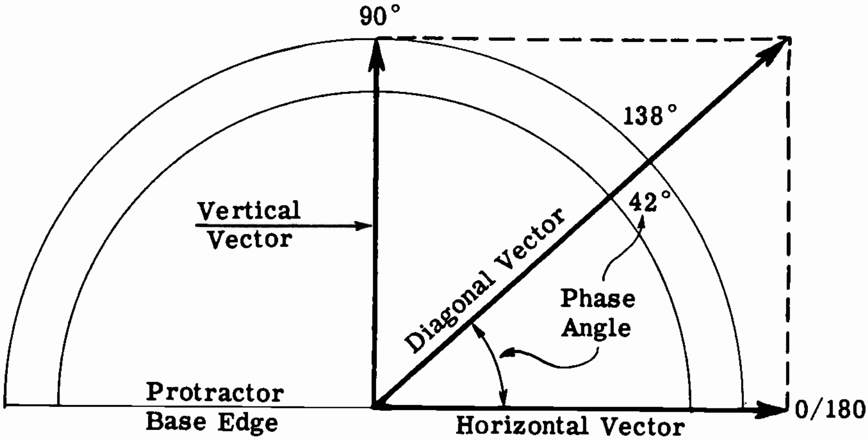
In addition to showing the value of the circuit impedance, the vector solution also shows the phase angle between the circuit current and voltage. The angle between the impedance vector Z and the resistance vector R is the "phase angle" of the circuit in degrees. This is the angle between the circuit voltage and current, and represents a current lag of 39 degrees.

current lags voltage

R and L Series Circuit Impedance (continued)

A protractor is an angle-measuring device utilizing a semi-circular double scale marked off in degrees.

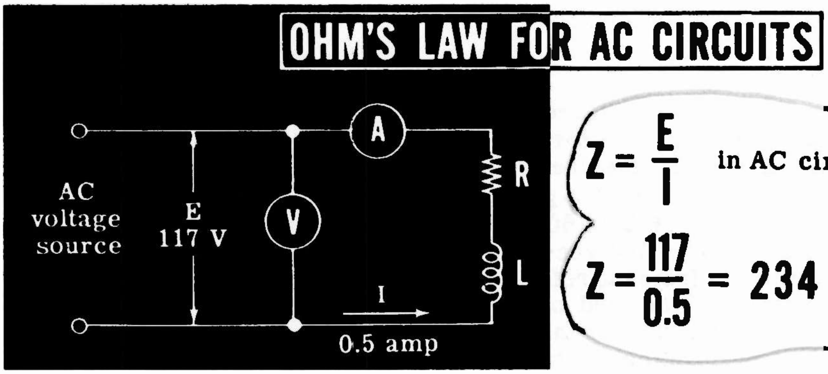
To measure the phase angle of a vector relative to a reference line, the horizontal edge of the protractor is lined up with the horizontal reference vector and the protractor vertical line is lined up with the vertical vector. The degree point at which the diagonal vector intersects the semi-circular scale is the phase angle of the diagonal vector. The angle is read between zero and 90 degrees, because the phase angle will never be less than zero or greater than 90 degrees.



USING A PROTRACTOR TO MEASURE PHASE ANGLE

R and L Series Circuit Impedance (continued)

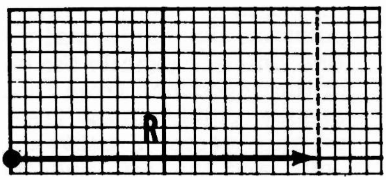
Ohm's law for AC circuits may also be used to find the impedance Z for a series circuit. In applying Ohm's law to an AC circuit, Z is substituted for R in the formula. Thus the impedance Z is equal to the circuit voltage E divided by the circuit current I. For example, if the circuit voltage is 117 volts, and the current is 0.5 ampere, the impedance Z is 234 ohms.



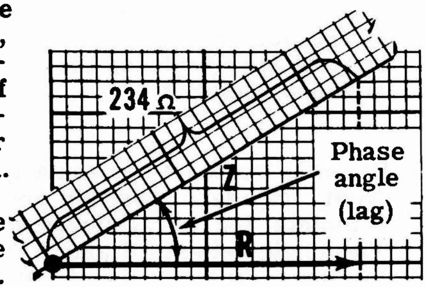
E = IR
V = IR

If the impedance of a circuit is found by applying Ohm's law for AC, and the value of R is known and X_L is unknown, the phase angle and the value of X_L may be determined graphically by using vectors. If the resistance in the circuit above is known to be 200 ohms, the vector solution is as follows:

1. Since the resistance is known to be 200 ohms, the resistance vector is drawn horizontally from the reference point. At the end of the resistance vector, a dotted line is drawn perpendicular to the resistance vector.



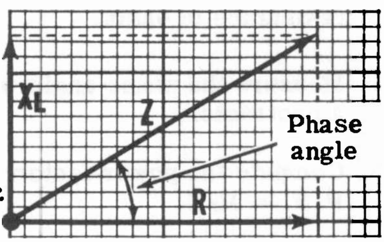
2. Using a straight edge marked to indicate the length of the impedance vector Z, find the point on the perpendicular dotted line which is exactly the length of the impedance vector from the reference point. Draw the impedance vector between that point and the zero position. The angle between the two vectors Z and R is the circuit phase angle, and the length of the dotted line between the ends of the two vectors represents X_L.



3. Complete the parallelogram by drawing a horizontal dotted line between the end of the vector Z and a vertical line drawn up from the reference point. X_L is this vertical line, and its length can be read by using the same scale. In the example shown, $X_L = 122\,\Omega$.

4. Measure the phase angle with a protractor.

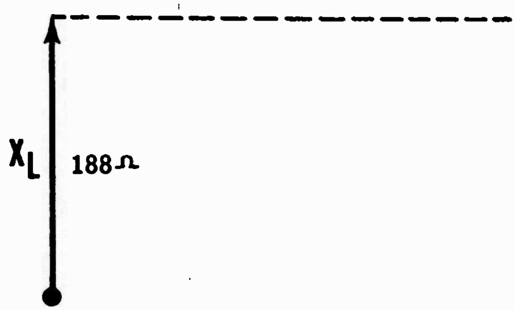
5. Divide R/Z = Power Factor = 200/234 = .85 or 85%.



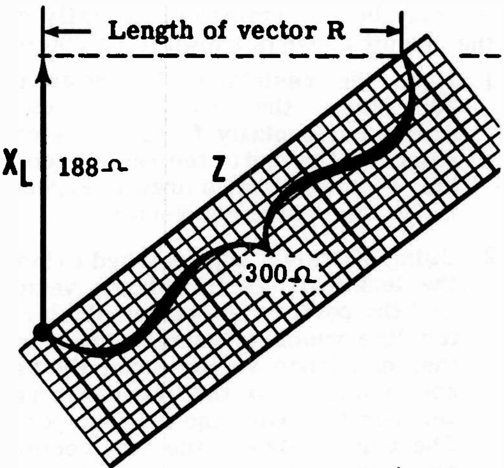
R and L Series Circuit Impedance (continued)

If the impedance and inductance are known, but the resistance is not known, both the phase angle and resistance may be found by using vectors. For example, the impedance is found to be 300 ohms by measuring the current and voltage and applying Ohm's law for AC. If the circuit inductance is 0.5 henry, the vector solution is as follows:

1. First the inductive reactance is computed by using the formula $X_L = 2\pi fL$. If the frequency is 60 cycles, then X_L is 188 ohms ($X_L = 6.28 \times 60 \times 0.5 = 188\Omega$). Draw the vector X_L vertically from the reference point. At the end of this vector, draw a horizontal dotted line perpendicular to the vector X_L.



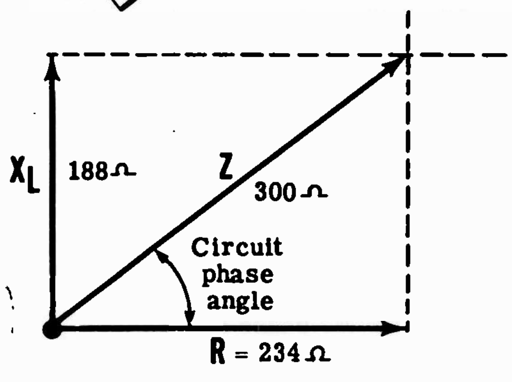
2. Using a straight edge marked to indicate the length of the impedance vector, find the point on the horizontal dotted line which is exactly the length of the impedance from the reference point. Draw the impedance vector Z between that point and the reference point. The distance between the ends of the vectors X_L and Z represents the length of the resistance vector R.



3. Draw the vector R horizontally from the zero position and complete the parallelogram. The angle between R and Z is the phase angle of the circuit in degrees, and the length of the vector R represents the resistance in ohms.

4. Measure the phase angle with a protractor.

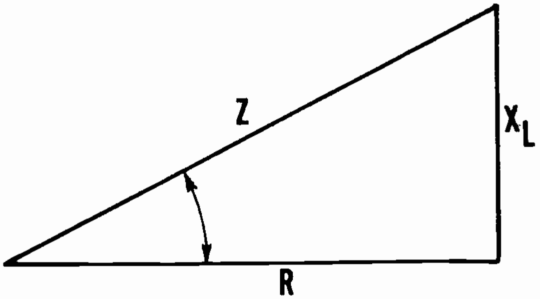
5. Compute the power factor.
   P. F. = R/Z



R and L Series Circuit Impedance (continued)

You have already learned how to calculate (by Ohm's Law) the impedance of a series circuit which is composed of a coil and a resistor, and which is connected to an AC voltage source. You will now learn how to calculate the impedance of such a circuit without the use of Ohm's Law, and without making measurements.

Assume, for this problem, that the inductive reactance X_L is 4 ohms and that the resistance is 3 ohms. The formula for finding the impedance in the circuit described is as follows:

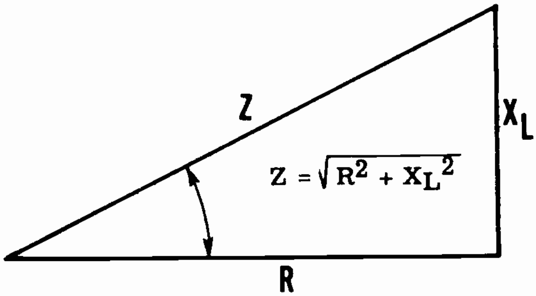


$$Z = \sqrt{R^2 + X_L{}^2}$$

Because you may not be familiar with the "square root" sign ($\sqrt{}$), and the "square" signs which are in position at the top right of the symbols for resistance and inductive reactance, these symbols or signs are explained below.

A simple way of showing mathematically that a number is to be multiplied once by itself, or "squared," is to place a numeral 2 at the upper right of the number in question. So that

$3^2 = 3 \times 3$ or 9
$5^2 = 5 \times 5$ or 25
$4^2 = 4 \times 4$ or 16
and $12^2 = 12 \times 12$ or 144, etc.



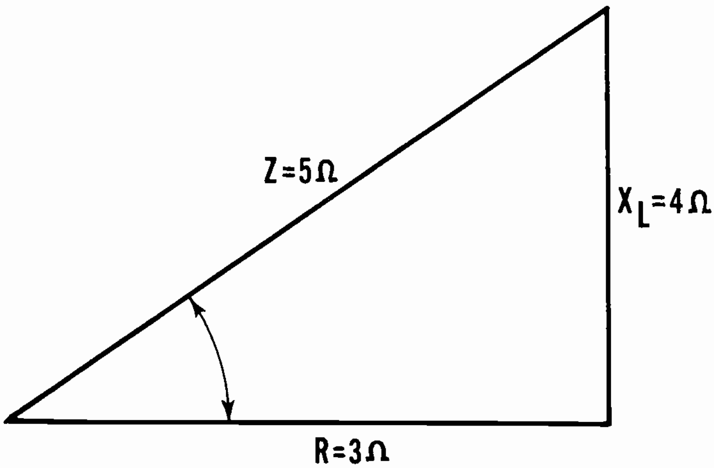
R and L Series Circuit Impedance (continued)

The square root sign, or $\sqrt{}$, indicates that you are to break down the enclosed figure to find a number which, when multiplied by itself, results in the original enclosed figure. Consider the problem of finding the square root of 144, shown mathematically, $\sqrt{144}$. What number multiplied by itself results in 144? The answer, of course, is 12. So that

$$\sqrt{144} = 12, \text{ and } \sqrt{36} = 6,$$
$$\sqrt{25} = 5, \text{ and } \sqrt{9} = 3, \text{ etc.}$$

The formula for impedance ($Z = \sqrt{R^2 + X_L{}^2}$) then, indicates that you must "square" the values for R and X_L, add the two resultant figures and take the square root of the total, in order to find the impedance, Z.

As given on the previous sheet, X_L is 4 ohms and R is 3 ohms. Find the impedance.



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

By substitution

$$Z = \sqrt{3^2 + 4^2} = \sqrt{9 + 16} = \sqrt{25} = 5$$

More often than not, the number enclosed by the square root symbol does not permit a simple answer without decimals. In that event it is necessary to find the square root which is closest to the desired numeral within the limits outlined by the instructor. For example, the instructor may elect to accept as correct an impedance value of five ohms even though the original figure required that the square root of 30 be found. (The $\sqrt{30}$ is actually equal to 5.47.) There are, of course, methods for finding accurate square root answers but these need not be dealt with here.

Power Factor

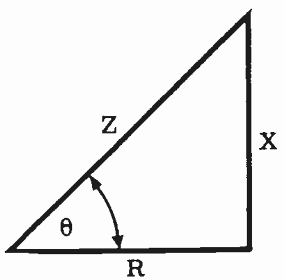
The concept of power, particularly with regard to the calculation of power factors in AC circuits, will become a very important consideration as the circuits you work with are made more complex. In DC circuits the expended power may be determined by multiplying the voltage by the current. A similar relationship exists for finding the amount of expended power in AC circuits, but certain other factors must be considered. In AC circuits the power is equal to the product of voltage and current only when the E and I are in phase. If the voltage and current waves are not in phase, the power used by the circuit will be somewhat less than the product of E and I.

A review of the following principles (most of which you already know) will be helpful later on, in the discussion.

1. Power is defined as the rate of doing work.
2. A watt is the unit of electrical power.
3. Apparent power is the product of volts and amperes in an AC circuit.
4. True power is the amount of power actually consumed by the circuit.
5. True power is equal to apparent power if the voltage and current are in phase.
6. True power is equal to zero if the voltage and current are out of phase by 90 degrees.
7. True power is equal to the apparent power multiplied by a figure called the "cosine of the phase angle." (This term will be explained shortly.)
8. The cosine of the phase angle is called the "power factor" and is often expressed as a decimal or percentage.

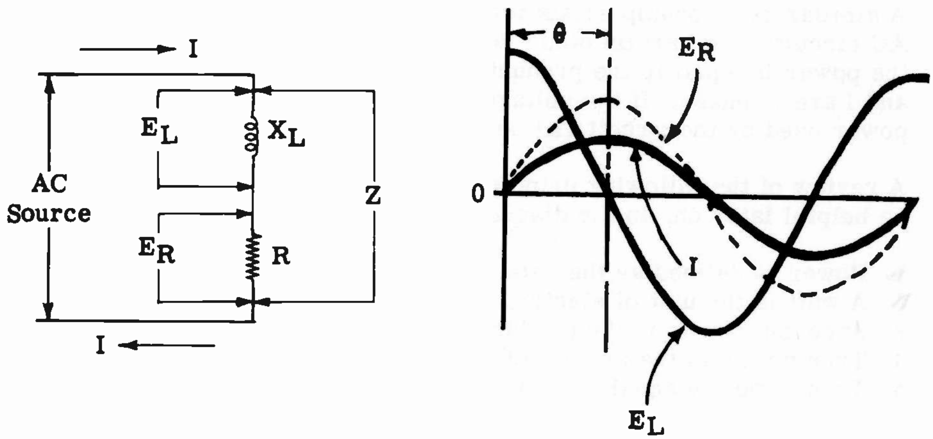
The power factor is important because it converts apparent power to true power. It is this true power, the kind that actually does work in the circuit, which will interest you most.

The cosine of the phase angle, or power factor, is explained with the help of the familiar impedance triangle diagram. The resistive component forms the base. The reactive component (X) forms the right angle with the base, and the third side called the "hypotenuse" is the resultant impedance (Z). The angle formed by the R and Z sides of the impedance triangle is called by the Greek letter θ (theta). The angle θ originally refers to the phase angle difference between the voltage across the resistor and the voltage across the coil in the diagram on the next sheet.

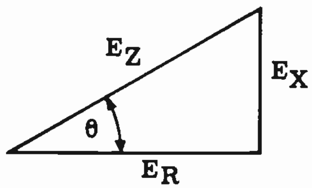


Power Factor (continued)

Theoretically, the voltage across the coil leads the current through the circuit by a phase angle of 90 degrees. E_L leads the voltage across the resistor because E_R is in phase with I.



In practical circuits a phase angle of 90 degrees is an impossibility because every coil (and wire) has some resistance, however small. It is this resistance, and the resistance placed in the circuit by design, which reduces the phase angle to something less than 90 degrees. Consider the voltage triangle of the circuit above. Each of the voltages noted may also be expressed



$E_Z = IZ$
$E_X = IX$
$E_R = IR$

as the product of the current times the resistance, reactance, or impedance, as the case may be. The term, cosine of the phase angle, refers to a ratio of E_R to E_Z and is expressed mathematically as

$$\text{Cos } \theta = \frac{E_R}{E_Z}$$

This formula is used just as well where impedance, resistance, and reactance are the prime considerations, because

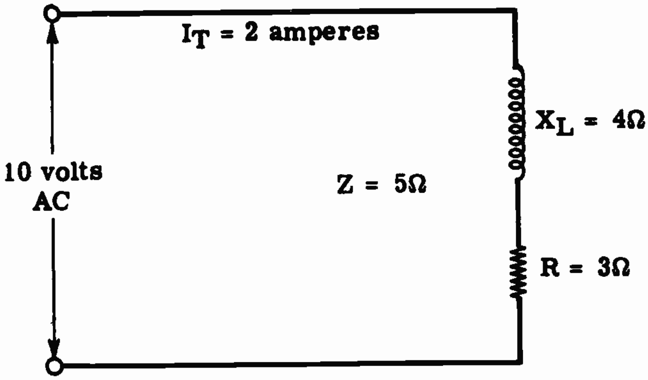
$$\text{Cos } \theta = \frac{E_R}{E_Z} = \frac{IR}{IZ} = \frac{R}{Z}$$

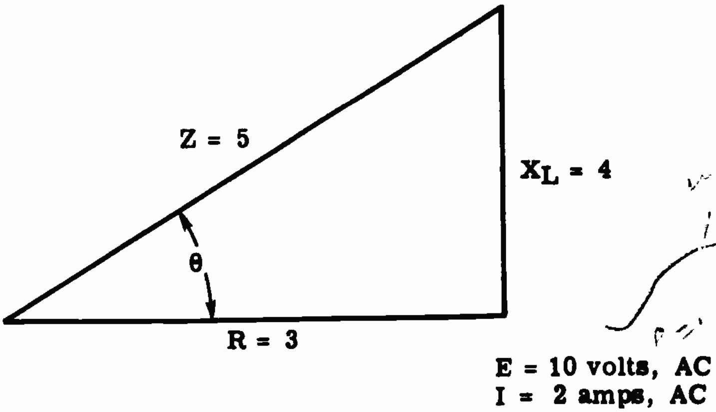
You now know all of the factors mentioned in points 7 and 8 on the previous sheet. The formula for true power should, therefore, present no difficulties. This formula is expressed mathematically as

$P = EI \text{ Cos } \theta$ or, $\text{Cos } \theta = \dfrac{P}{EI}$ or, $EI = \dfrac{P}{\text{Cos } \theta}$

Power Factor (continued)

Suppose that you wish to find the amount of power expended (true power) in a circuit where the impedance is five ohms, the resistance is three ohms, and the inductive reactance is four ohms. The impressed voltage is ten volts AC, and the current is two amperes.





The formula for true power is P = EI Cos θ. With reference to the impedance triangle the Cos θ is equal to the ratio of R divided by Z, or

$$\text{Cos } \theta = \frac{R}{Z} = \frac{3}{5} = .60 \text{ or } 60\%$$

Substituting in the formula for true power

$$P = EI \text{ Cos } \theta$$
$$P = 10 \times 2 \times .6$$
$$P = 12 \text{ watts of power expended}$$

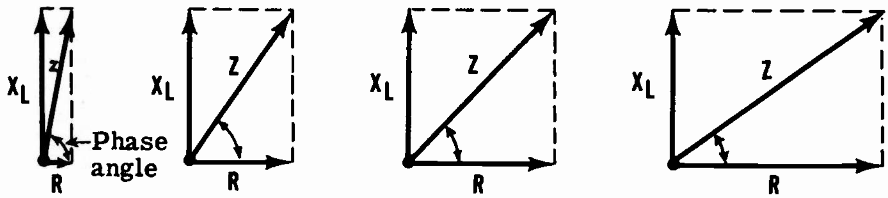
The components in the circuit must be chosen of such size that they will be able to dissipate twelve watts of power at the very minimum, or burnout will occur.

R and L Series Circuits Impedance Variation

The impedance of a series circuit containing only resistance and inductance is determined by the vector addition of the resistance and the inductive reactance. If a given value of inductive reactance is used, the impedance varies as shown when the resistance value is changed.

How Impedance Varies

WHEN X_L IS A FIXED VALUE AND R IS VARIED

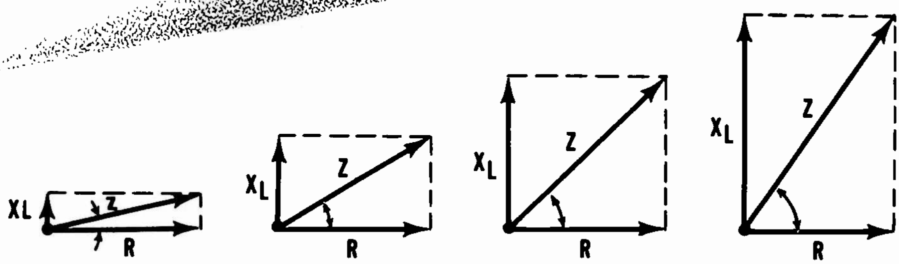


Impedance increases
and the phase angle decreases
as R increases

Similarly, if a given value of resistance is used, the impedance varies as shown when the inductive reactance is changed.

How Impedance Varies

WHEN R IS A FIXED VALUE AND X_L IS VARIED



Impedance increases and the phase angle increases
as X_L increases

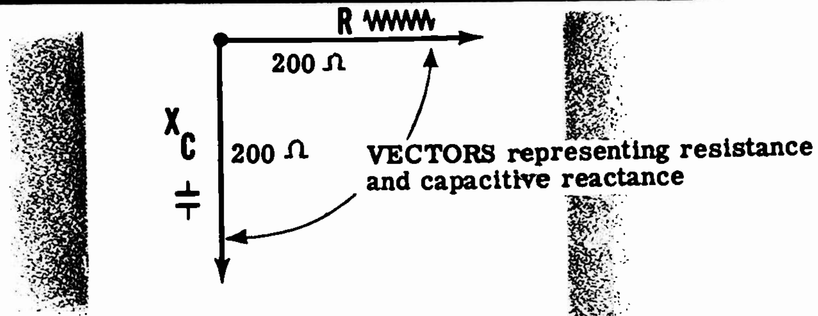
When the resistance equals zero the impedance is equal to X_L, and when the inductive reactance equals zero the impedance is equal to R. While the value of Z may be determined by means of a complex mathematical formula, you will use the practical methods—a vector solution or Ohm's law for AC circuits.

R and C Series Circuit Impedance

If your AC series circuit consists of resistance and capacitance in series, the total opposition to current flow (impedance) is due to two factors, resistance and capacitive reactance. The action of capacitive reactance causes the current in a capacitive circuit to lead the voltage by 90 degrees, so that the effect of capacitive reactance is at right angles to the effect of resistance. While the effects of both inductive and capacitive reactance are at right angles to the effect of resistance, their effects are exactly opposite—inductive reactance causing current to lag and capacitive reactance causing it to lead the voltage. Thus the vector X_C, representing capacitive reactance, is still drawn perpendicular to the resistance vector, but is drawn down rather than up from the zero position.

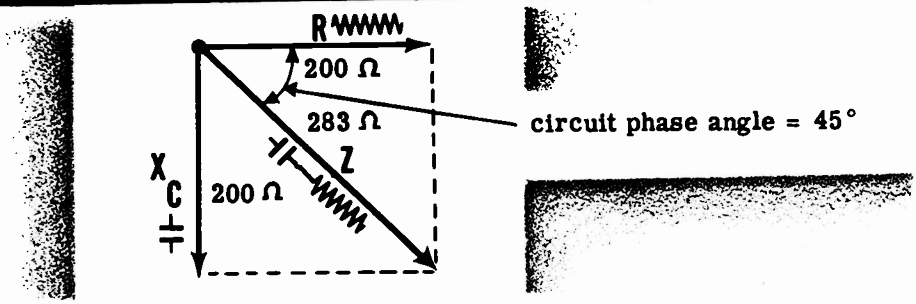
The impedance of a series circuit containing R and C is found in the same manner as the impedance of an R and L series circuit. For example, suppose that in your R and C series circuit R equals 200 ohms and X_C equals 200 ohms. To find the impedance, the resistance vector R is drawn horizontally from a reference point. Then a vector of equal length is drawn downward from the reference point at right angles to the vector R. This vector X_C represents the capacitive reactance and is equal in length to R since both R and X_C equal 200 ohms.

REPRESENTING R AND X_C AS VECTORS



To complete the vector solution, the parallelogram is completed and a diagonal drawn from the reference point. This diagonal is the vector Z and represents the impedance in ohms (283 ohms). The angle between the vectors R and Z is the phase angle of the circuit, indicating the amount in degrees that the current leads the voltage.

COMBINING VECTORS R AND X_C TO FIND THE IMPEDANCE

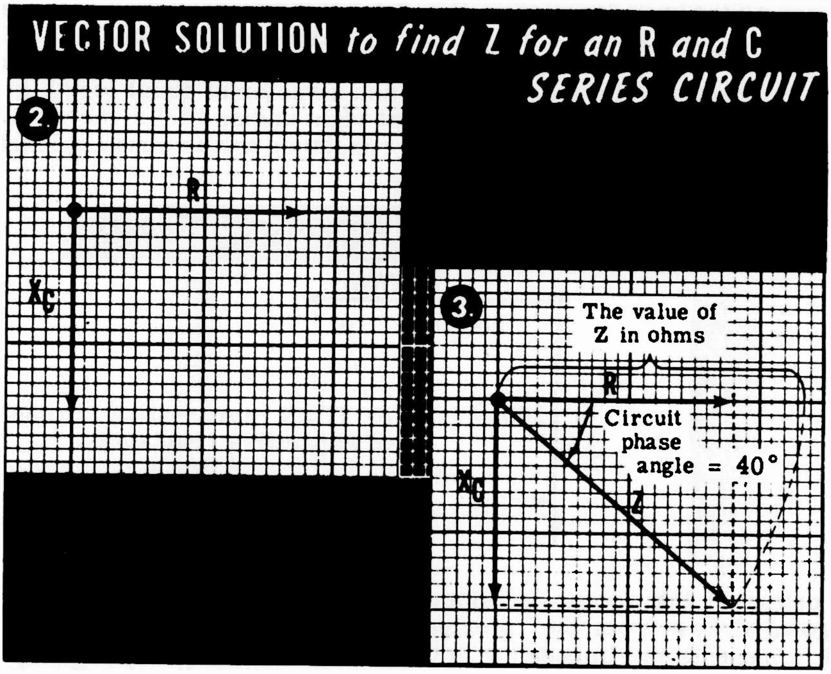


R and C Series Circuit Impedance (continued)

R and C series circuit impedances can be found either by using the vector solution or by application of Ohm's law. To find the impedance Z by using a vector solution, you should perform the steps outlined.

1. Compute the value of X_C by using the formula $X_C = \frac{1}{2\pi fC}$. In this formula 2π is a constant equal to 6.28, f is the frequency in cycles per second and C is the capacitance in farads.

2. Draw vectors R and X_C to scale on graph paper, using a common reference point for the two vectors. R is drawn horizontally to the right from the reference point and X_C is drawn downward from the reference point, perpendicular to the resistance vector R.



3. Using dotted lines, a parallelogram is completed and a diagonal drawn from the reference point to the intersection of the dotted lines. The length of this diagonal represents the impedance Z as measured to the same scale as that used for R and X_C. The angle between the vectors R and Z is the phase angle between the circuit current and voltage.

4. Measure the angle in degrees with a protractor.

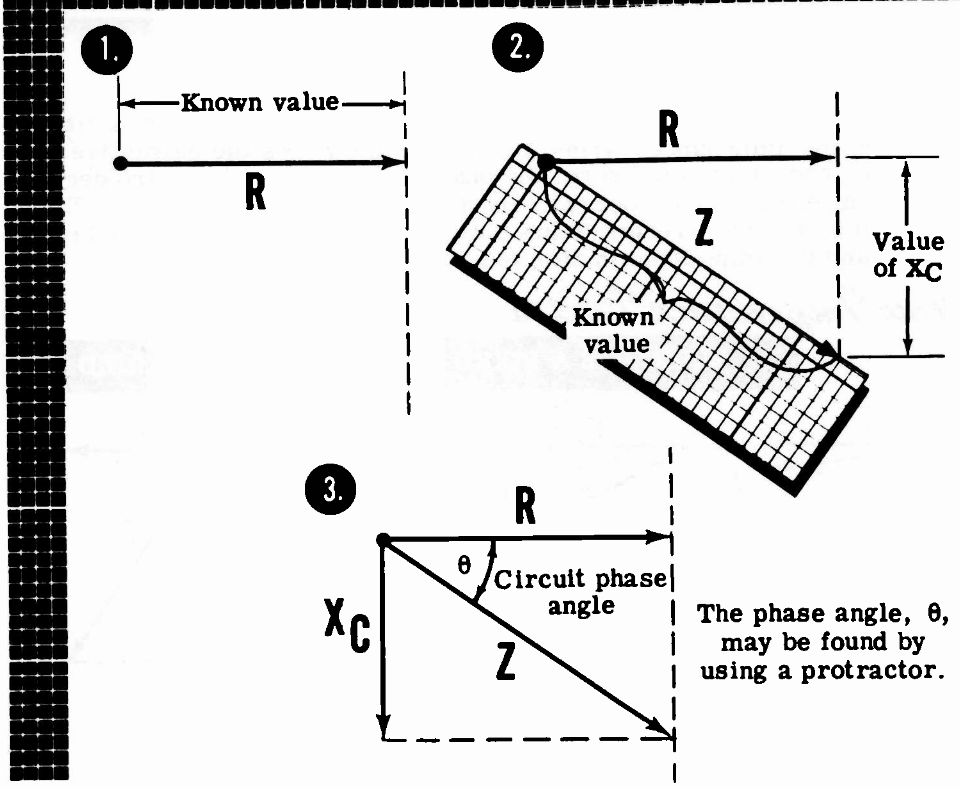
You can also use Ohm's law ($Z = \frac{E}{I}$) to find Z. After measuring the circuit current and voltage, the impedance in ohms can be found by dividing the voltage by the current. For example, if the circuit voltage is 117 volts and 0.1 ampere of current flows through an AC series circuit consisting of R and C, the impedance is 1170 ohms (117 ÷ 0.1 = 1170 ohms).

R and C Series Circuit Impedance (continued)

When the value of either R or X_C is unknown, but the value of Z is known, you can find the unknown value by vector solution.

If you find Z by applying Ohm's law to the AC circuit, and the value of R is known and X_C is unknown, the first step in finding X_C is to draw the resistance vector R to scale. Next a dotted line is drawn downward at the end of and perpendicular to the vector R. A straight edge, marked to indicate the length of the impedance vector Z, is used to find the point on the dotted line which is exactly the length of the impedance vector Z from the reference point. Draw the vector Z between that point and the reference point. Complete the parallelogram with the value of X_C being equal to the distance between the ends of the vectors R and Z. If Z and X_C are known but R is unknown, the vector X_C is first drawn to scale. A horizontal dotted line is drawn to the right, at the end of and perpendicular to the vector X_C. Then a straight edge is used as before to find the point on this dotted line which is exactly the length of the impedance vector Z from the reference point. Draw the vector Z between that point and the reference point. Complete the parallelogram, with the value of R being equal to the distance between the ends of the vectors X_C and Z.

VECTOR SOLUTION to find X_C



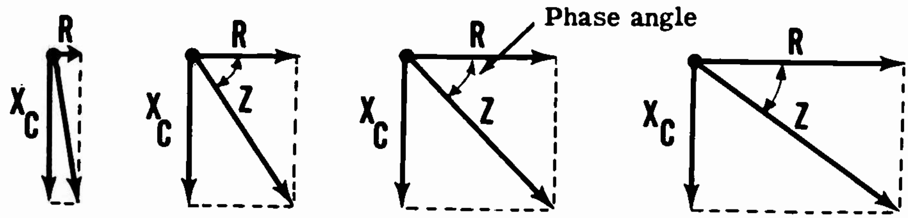
The phase angle, θ, may be found by using a protractor.

R and C Series Circuit Impedance (continued)

The ratio of R to X_C determines both the amount of impedance and the phase angle in series circuits consisting only of resistance and capacitance. If the capacitive reactance is a fixed value and the resistance is varied, the impedance varies as shown. When the resistance is near zero, the phase angle is nearly 90 degrees and the impedance is almost entirely due to the capacitive reactance; but, when R is much greater than X_C, the phase angle approaches zero degrees and the impedance is affected more by R than X_C.

How Impedance Varies

WHEN X_C IS A FIXED VALUE AND R IS VARIED

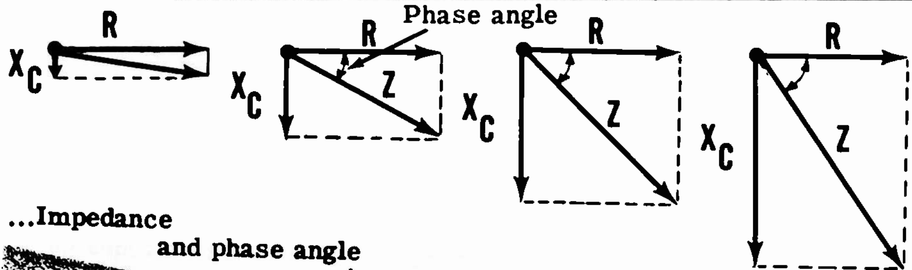


...Impedance increases and phase angle decreases as R increases

If your circuit consists of a fixed value of resistance and the capacitance is varied, the impedance varies as shown below. As the capacitive reactance is reduced toward zero, the phase angle approaches zero degrees and the impedance is almost entirely due to the resistance; but, as X_C is increased to a much greater value than R, the phase angle approaches 90 degrees and the impedance is affected more by X_C than R.

How Impedance Varies

WHEN R IS A FIXED VALUE AND X_C IS VARIED



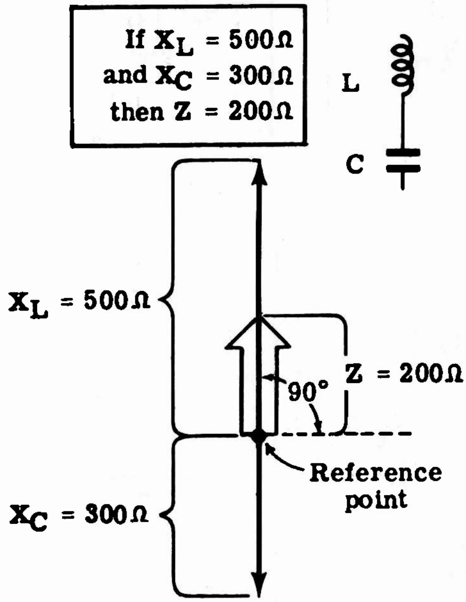
...Impedance and phase angle increases as X_C increases

L and C Series Circuit Impedance

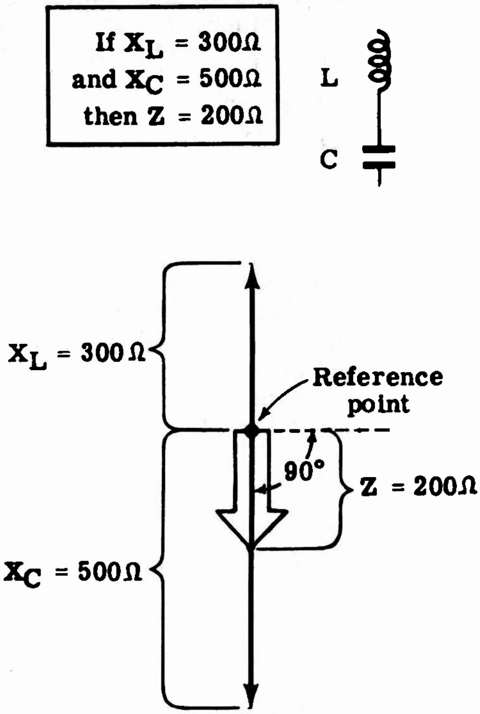
In AC series circuits consisting of inductance and capacitance, with only negligible resistance, the impedance is due to inductive and capacitive reactance only. Since inductive and capacitive reactances act in opposite directions, the total effect of the two is equal to their difference. For such circuits, Z can be found by subtracting the smaller value from the larger. The circuit will then act as an inductive or a capacitive reactance (depending on which is larger) having an impedance equal to Z. For example, if X_L = 500 ohms and X_C = 300 ohms, the impedance Z is 200 ohms and the circuit acts as an inductance having an inductive reactance of 200 ohms. If the X_L and X_C values were reversed, Z would still equal 200 ohms, but the circuit would act as a capacitance having a capacitive reactance of 200 ohms.

The relationships of the above examples are shown below. Z is drawn on the same axis as X_L and X_C and represents the difference in their values. The phase angle of the L and C series circuit is always 90 degrees except when $X_L = X_C$, but whether it is leading or lagging depends on whether X_L is greater or less than X_C. The phase angle is the angle between Z and the horizontal axis.

COMBINING VECTORS X_L AND X_C



Phase angle is 90° — current lagging. Circuit acts as an inductance.



Phase angle is 90° — current leading. Circuit acts as a capacitance.

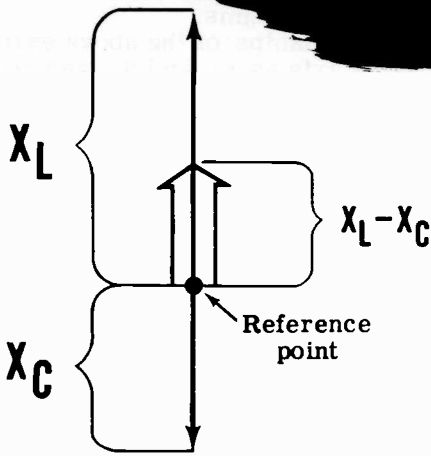
R, L and C Series Circuit Impedance

The impedance of a series circuit consisting of resistance, capacitance and inductance in series depends on three factors: R, X_L and X_C. If the values of all three factors are known, impedance Z may be found as follows:

Combining Vectors R, X_L and X_C to find the Impedence

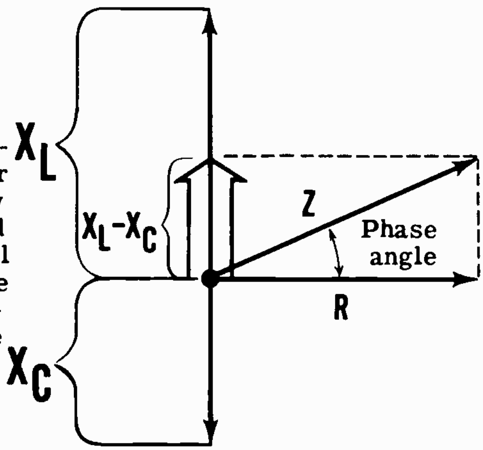
Combine X_L and X_C

1. Draw vectors X_L and X_C to scale vertically from the reference point, and subtract the smaller vector from the larger. The difference is the new vector and should be drawn to scale on the perpendicular axis as shown. Perform a vector addition by subtracting a length equal to the shorter vector from the longer vector.



Combine R and (X_L - X_C)

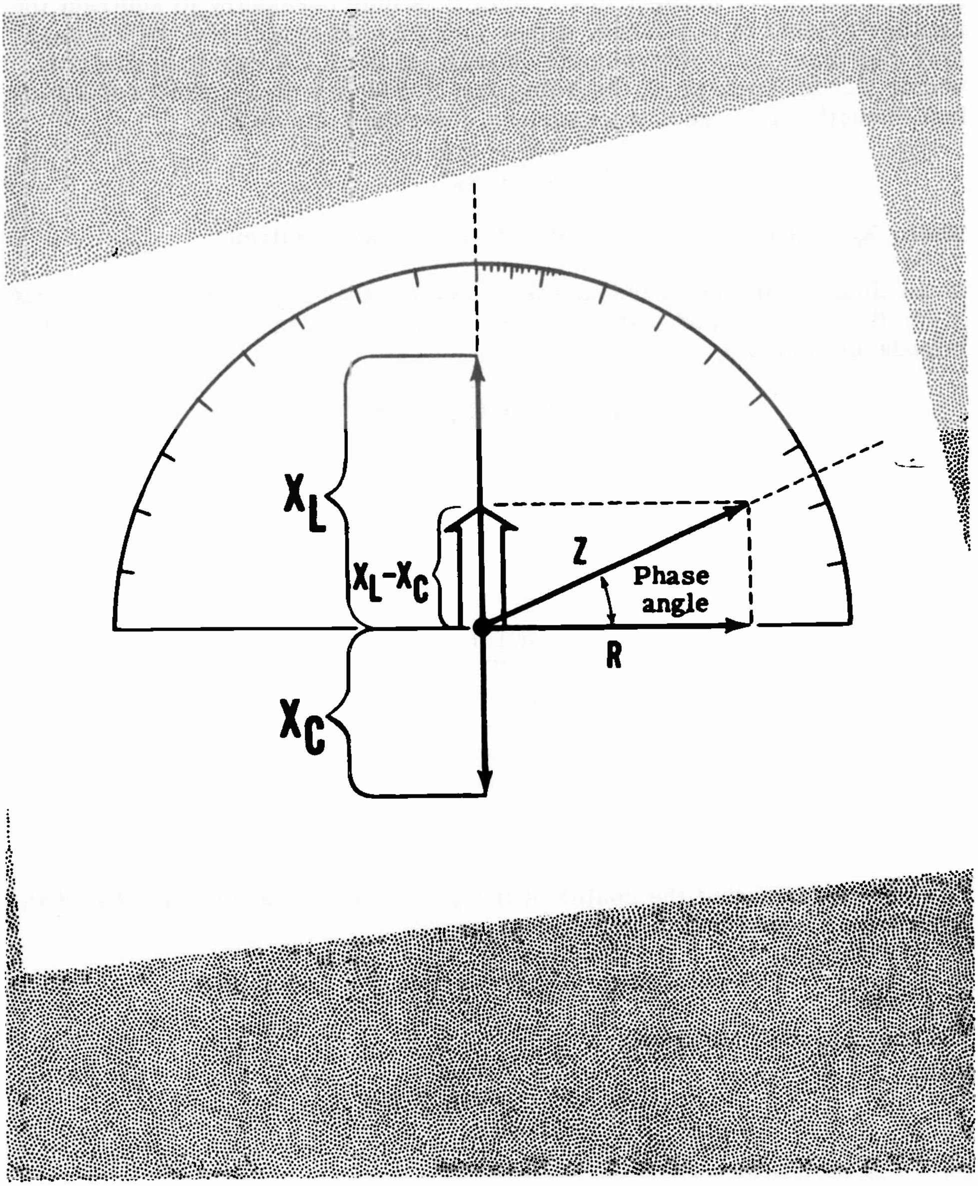
2. Draw the vector R to scale horizontally, and combine it with the vector obtained in the solution of Step 1 by completing the parallelogram and drawing the diagonal. This diagonal is the vector Z, representing the circuit impedance. The angle between the vectors R and Z is the circuit phase angle.



You can also find the impedance of the circuit by applying Ohm's law for AC circuits, after measuring the circuit current and voltage.

R, L and C Series Circuit Impedance (continued)

On the previous sheet you learned how to combine vectors R, X_L and X_C to find the impedance. It is a simple matter to find the phase angle between the impedance and the resistance by using a protractor. Superimpose the protractor on the vector diagram below.



Take the angle reading at the point where the impedance line crosses the protractor scale.

R, L and C Series Circuit Impedance (continued)

The impedance of a circuit which contains R, L and C components may also be calculated by using a variation of the impedance formula $Z = \sqrt{R^2 + X^2}$. You have learned that it makes no difference if the reactive component, X, is inductive or capacitive in nature; the impedance is found in the same way, using the same formula for Z. Also, when both inductive and capacitive reactance are present in a circuit it is only necessary to subtract the smaller amount of reactance, either inductive or capacitive, as the case may be, from the larger amount and then draw in the resultant diagonal vector Z. In calculating the value for impedance in a circuit containing both inductive and reactive components use the formula

$$Z = \sqrt{R^2 + X_e{}^2}$$

where X_e is equal to $X_L - X_C$ or vice versa, as required.

In the diagram on the previous sheet, assume that X_L is seven ohms, that X_C is three ohms, and that R is three ohms. Placing these values in the impedance formula, we find

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

$$Z = \sqrt{3^2 + (7 - 3)^2} = \sqrt{3^2 + 4^2}$$

$$Z = \sqrt{9 + 16} = \sqrt{25}$$

$$Z = 5 \text{ ohms}$$

You will now review the method for finding the power factor and for using it to obtain true power dissipation. The apparent power is simply the voltage times the current. When this apparent power is multiplied by the cosine of the phase angle the result is the true power value. Using an impedance triangle, find the power factor and true power dissipation in a circuit which is composed of an equivalent reactance of four ohms, a resistance of three ohms, an impedance of five ohms, and which has a voltage of 2.5 volts and a current of 500 milliamps.

You have learned that the cosine of the phase angle is simply a ratio of the resistance divided by the impedance, so that

$$\text{Cosine of phase angle } \theta = \frac{R}{Z} = \frac{3}{5} = .60 \text{ or } 60\%$$

The formula for true power is

$$P = EI \cos \theta = 2.5 \times .5 \times .6$$
$$P = .75 \text{ watt}$$

Demonstration—Series Circuit Impedance

To see how series circuit impedance can be computed, by using vectors or by applying Ohm's law for AC to the circuit, you will participate in a demonstration of series circuit impedance. You will see how vector solutions are used to obtain quickly the approximate values of series circuit impedance.

You will see how the AC impedance is obtained by applying Ohm's law to various circuits and checking the computed impedances.

Using the 5-henry inductance, the 1-mfd capacitor and the 2000-ohm resistor, the instructor will demonstrate the use of vectors in finding circuit impedance for the various types of AC series circuits. Although the 5-henry filter choke used for inductance actually has a DC resistance of about 60 ohms, this value is negligible in comparison to the 2000 ohm resistor and will not be considered. To find the impedance of a circuit, the inductive and capacitive reactances must first be computed from the known inductance and capacitance values.

Frequency = 60 cycles

Finding X_L for a 5-henry inductance

$$X_L = 2\pi fL$$
$$X_L = 6.28 \times 60 \times 5$$
$$X_L = 1884$$

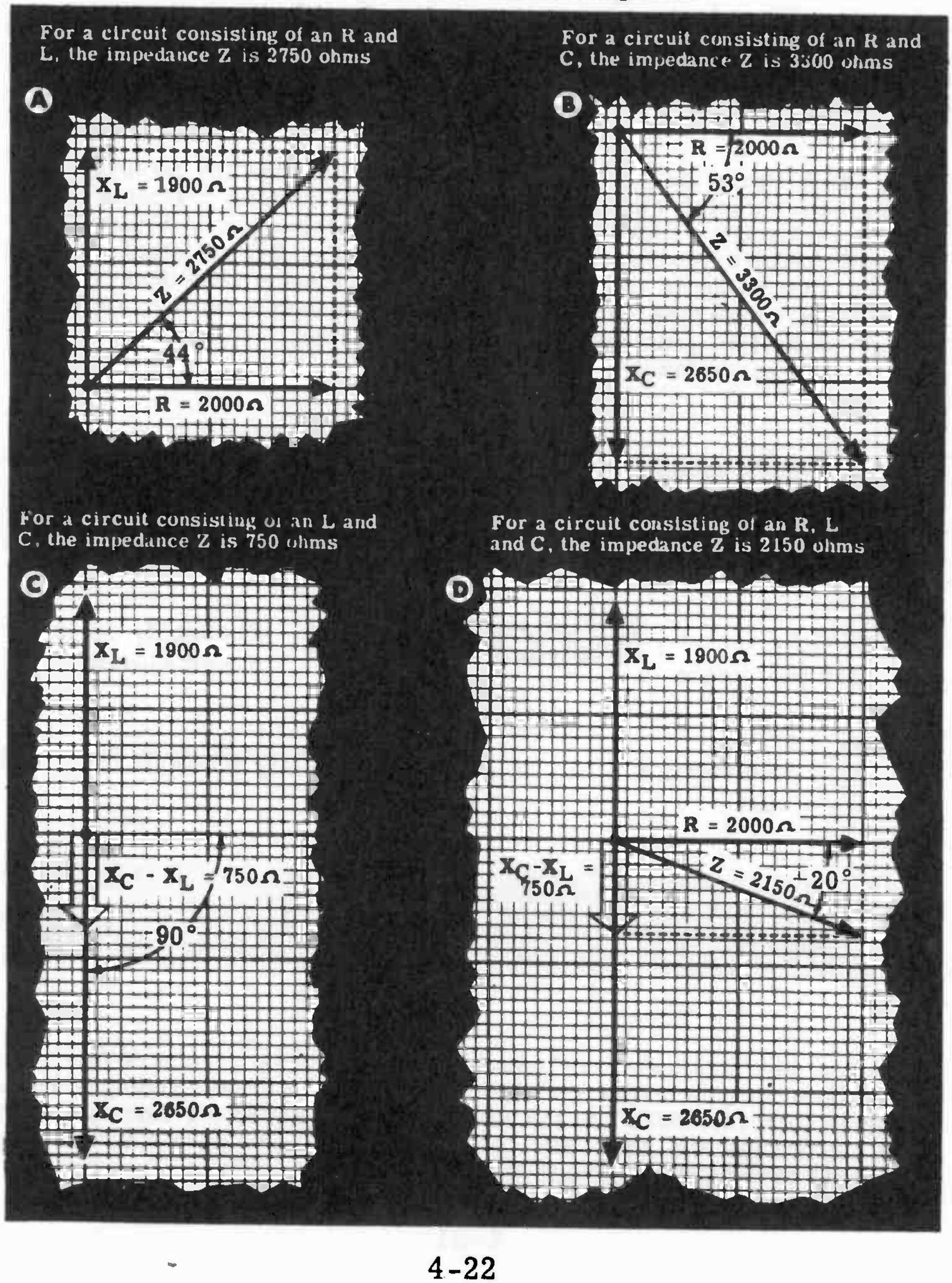
Finding X_C for a 1-mfd capacitor

$$X_C = \frac{1}{2\pi fC}$$
$$X_C = \frac{1}{6.28 \times 60 \times 0.000001} = \frac{1}{0.000377}$$
$$X_C = 2650$$

First the instructor uses the inductive and capacitive reactance formulas to obtain the values for X_L and X_C. To check your understanding of these formulas, find the inductive and capacitive reactances for inductances of 2 and 12 henries and capacitances of 2 and 5 mfd. Compare your answers with those obtained by others in the class.

Demonstration—Series Circuit Impedance (continued)

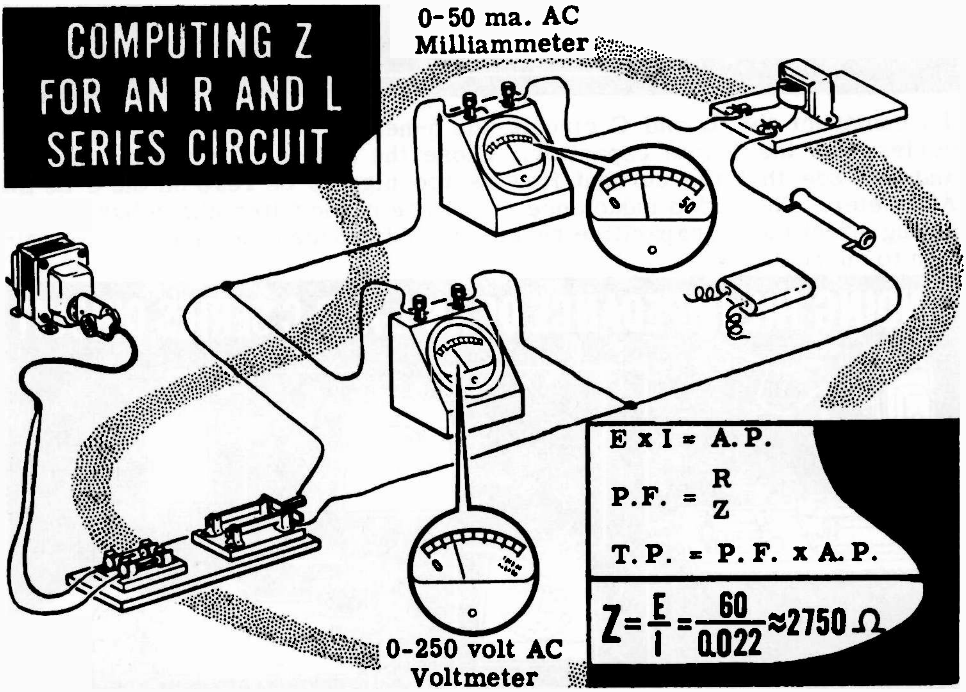
Using the computed values of X_L and X_C (X_L = 1884Ω and X_C = 2650Ω) and the known value of R (2000 ohms), the instructor next finds the value Z for each of the various types of series circuits by means of vector solution. (For graphical purposes, values of X_L, X_C and Z are rounded off to the nearest 50 ohms to make scale drawing possible. For example, the value used for X_L is 1900 ohms and the value used for X_C is 2650 ohms.) A protractor is used to measure phase angle in degrees.



Demonstration—Ohm's Law for AC Circuits

To check the computed impedance values for the various types of series circuits, the instructor connects the 2000-ohm resistor, 5-henry filter choke and 1-mfd capacitor to form the various circuits in turn. Each circuit is connected to the AC power line separately, and current and voltage are measured. These values are used to compute Z by using Ohm's law ($Z = \frac{E}{I}$). The Ohm's law values are then compared to vector solutions.

The 2000-ohm resistance, 5-henry choke, a switch, a fuse and a 0-50 ma. AC milliammeter are connected in series across the AC power line through the step-down autotransformer to form a series R and L circuit. A 0-200 volt range AC voltmeter is connected across the autotransformer to measure the circuit voltage. With the switch closed, you see that the voltmeter reads approximately 60 volts and the milliammeter reads about 22 ma. The Ohm's law value of Z is about 2750 ohms ($60 \div 0.022 \approx 2750$), and you see that the two methods of finding Z result in approximately equal values for Z. (The meter readings you observe will vary somewhat from those given due to variations in line voltage, meter accuracy and in the rating of the resistors, capacitors and chokes used. Thus the value of Z actually obtained will vary slightly in each case from the values given.)

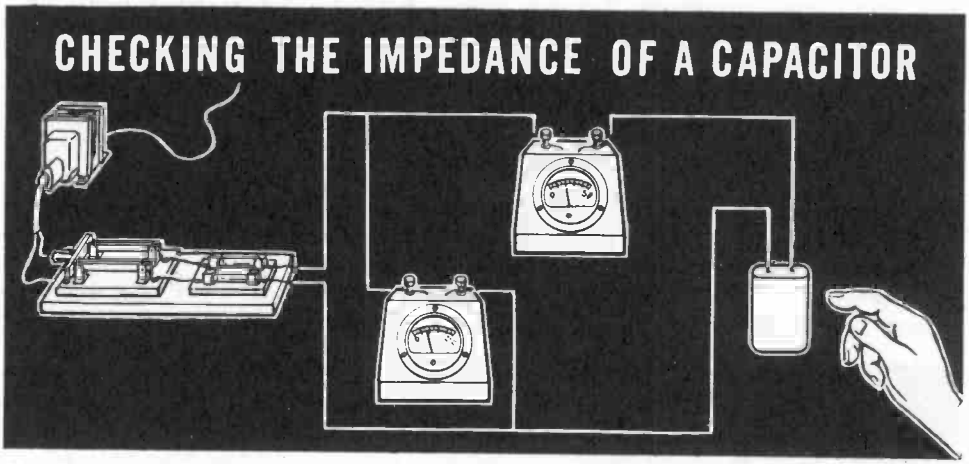


To check the impedance of the R and C series circuit, the instructor removes the 5-henry choke from the circuit and replaces it with the 1-mfd capacitor. With the switch closed, the voltmeter reading again is about 60 volts and the milliammeter reading is about 19 ma., resulting in an Ohm's law value of approximately 3300 ohms for Z ($60 \div 0.019 \approx 3300$).

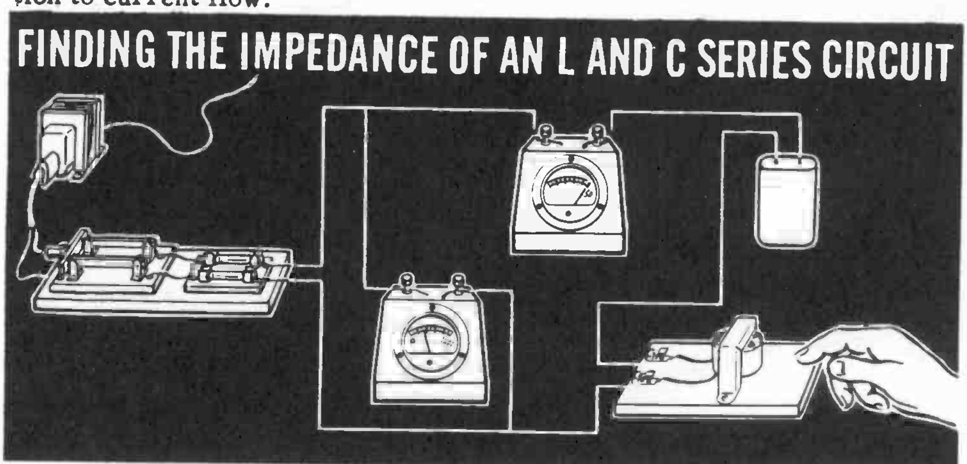
Demonstration—Ohm's Law for AC Circuits (continued)

Next the instructor demonstrates how inductive and capacitive reactance oppose each other.

The 2000-ohm resistor is removed from the circuit. With the switch closed you see that the voltage is still about 60 volts while the indicated current is about 23 ma. The Ohm's law value of the impedance then is approximately 2650 ohms ($60 \div 0.023 \approx 2650$). Since only capacitance is used in the circuit, the value of Z is equal to X_C.



To construct the L and C circuit, the 5-henry filter choke is inserted in series with the 1-mfd capacitor. Close the switch only for an instant, and you see that the current flow is too high to be read on the 0-50 ma. AC meter. The added inductance reactance of the filter choke has a canceling effect on the capacitive reactance and reduces the circuit's opposition to current flow.

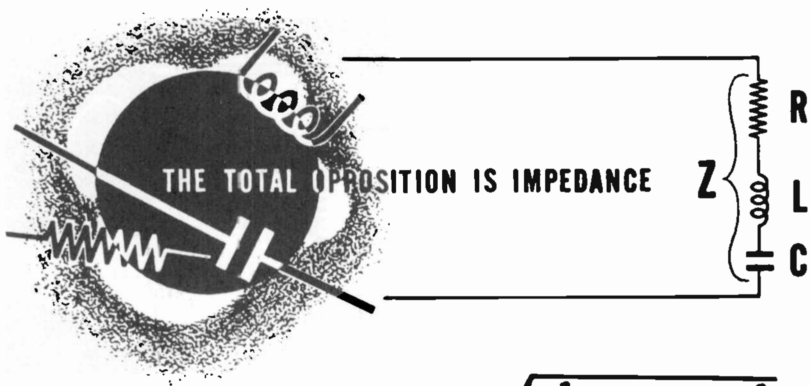


The 2000-ohm resistor is added to the circuit in series with the 5-henry filter choke and the 1-mfd capacitor to form an R, L and C series circuit. With the switch closed, the indicated current is about 28 ma. and the voltage is 60 volts. For the R, L and C series circuit, the Ohm's law value of impedance is 2150 ohms ($60 \div 0.028 \approx 2150$).

Review of Series Circuit Impedance

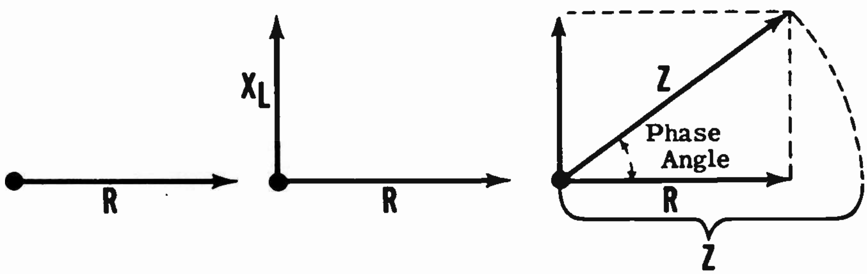
Suppose you review what you have found out about impedance and the methods used to find the value of impedance.

<u>IMPEDANCE</u> — The total opposition to the flow of current in an AC circuit.



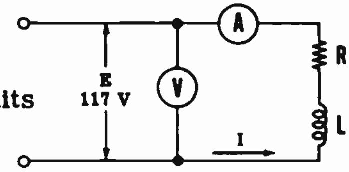
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Vector solution to find impedance and use of protractor to find phase angle.



Ohm's Law for AC Circuits.

$$Z = \frac{E}{I} \text{ in AC circuits}$$



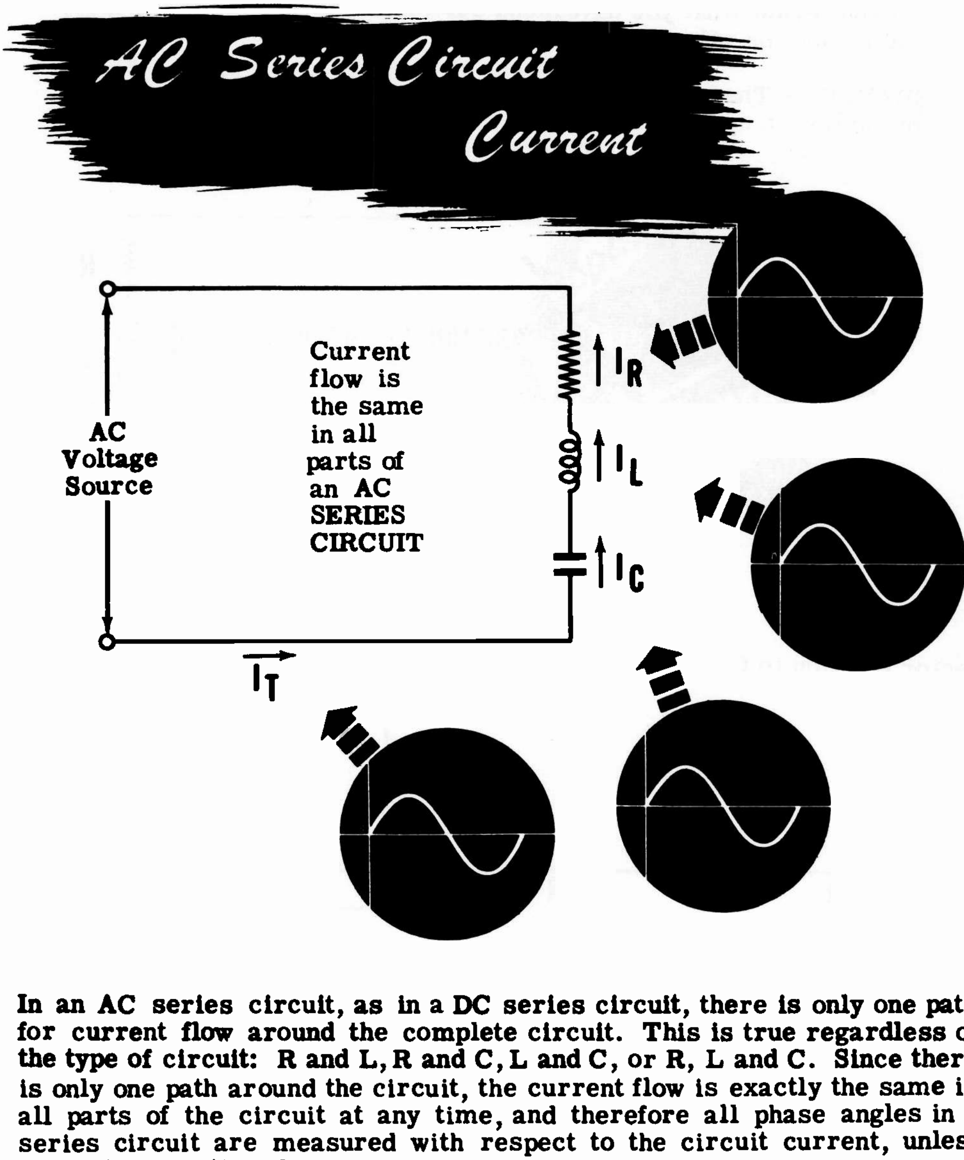
Formulas For Power and Power Factor

$E_T \times I_T = \text{A. P.}$

$\text{P. F.} = \frac{R}{Z}$

$\text{T. P.} = \text{P. F.} \times \text{A. P.}$

Current Flow in AC Series Circuits



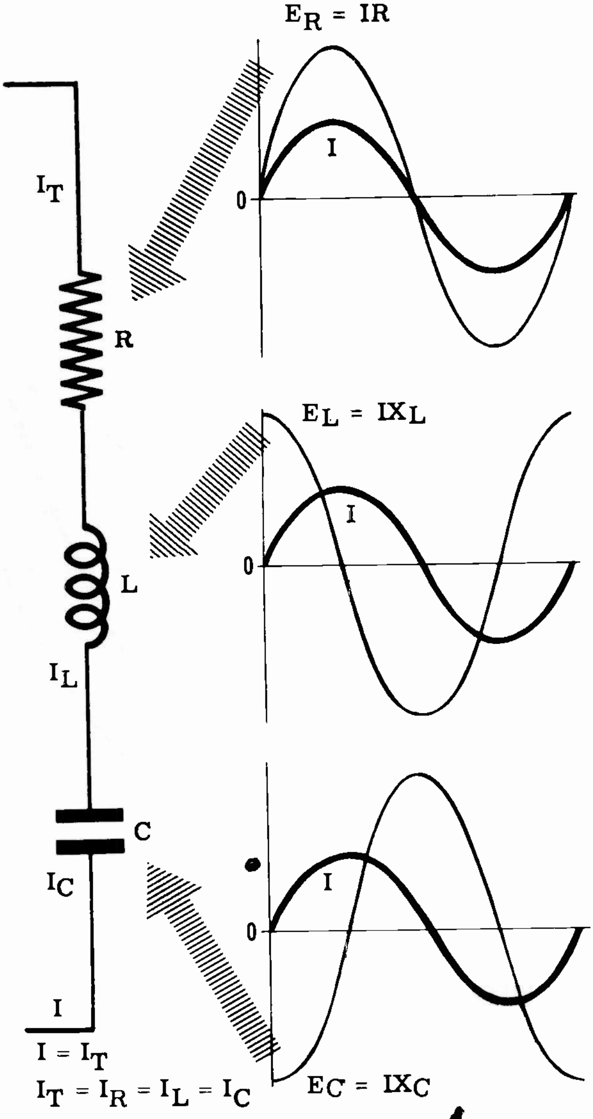
In an AC series circuit, as in a DC series circuit, there is only one path for current flow around the complete circuit. This is true regardless of the type of circuit: R and L, R and C, L and C, or R, L and C. Since there is only one path around the circuit, the current flow is exactly the same in all parts of the circuit at any time, and therefore all phase angles in a series circuit are measured with respect to the circuit current, unless otherwise mentioned.

Thus in a circuit containing R, L and C—such as the one illustrated—the current which flows into the capacitor to charge it will also flow through the resistor and the inductor. When the current flow reverses in the capacitor, it reverses simultaneously in the inductor and in the resistor. If you plot the current waveforms I_R, I_L and I_C for the resistor, inductor and capacitor in such a circuit, the three waveforms are identical in value and phase angle. The total circuit current, I_T, is also identical to these three waveforms both in value and phase angle, since $I_T = I_R = I_L = I_C$.

Voltages in AC Series Circuits

Just as the impedance of an AC series current cannot be found by adding the values of R, X_L and X_C directly, the total voltage, E_T, of an AC series circuit cannot be found by adding the individual voltages E_R, E_L and E_C across the resistance, inductance and capacitance of the circuit. They cannot be added directly because the individual voltages across R, L and C are not in phase with each other as shown below.

AC SERIES CIRCUIT VOLTAGE



The voltage E_R across R is in phase with the circuit current, since current and voltage are in phase in pure resistive circuits.

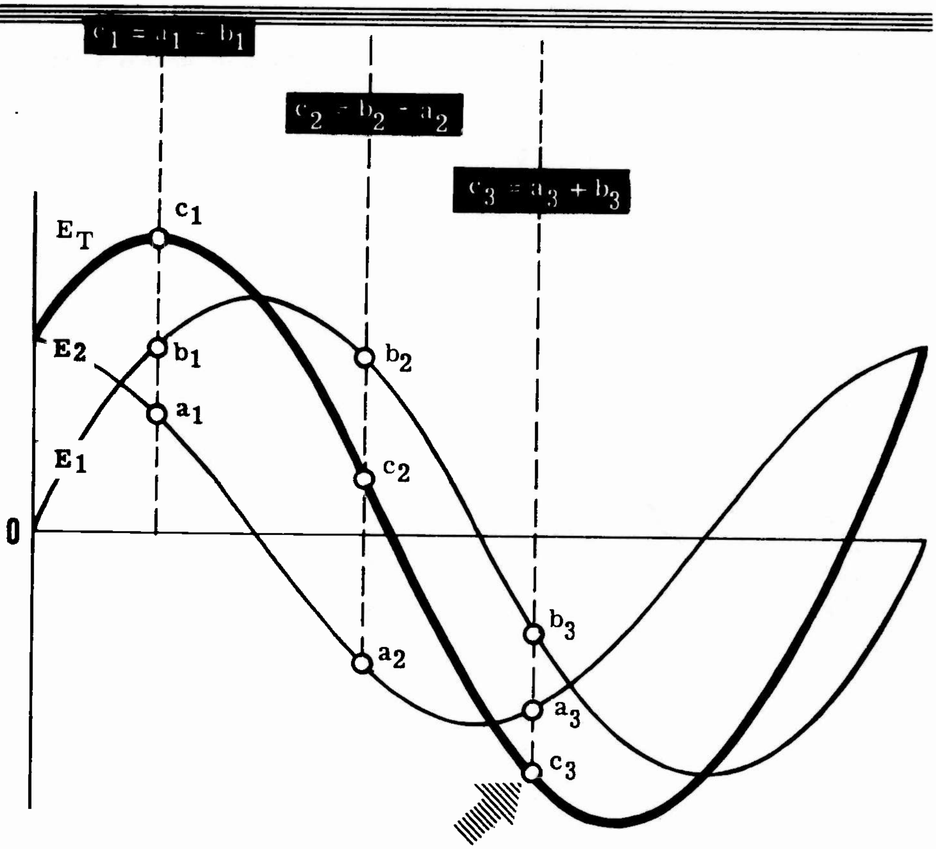
The voltage E_L across L leads the circuit current by 90 degrees, since current lags the voltage by 90 degrees in purely inductive circuits. Thus E_L crosses the zero axis going in the same direction, 90 degrees before the current.

The voltage E_C across C lags the circuit current by 90 degrees since current leads the voltage by 90 degrees in purely capacitive circuits. Thus E_C crosses the zero axis, going in the same direction, 90 degrees after the current wave.

Voltages in AC Series Circuits (continued)

To find the total voltage in a series circuit, the instantaneous values of the individual voltages for a particular moment are added together to obtain the instantaneous values of the total voltage waveform. Positive values are added directly as are negative values, and the difference between the total positive and negative values for a given moment is the instantaneous value of the total voltage waveform for that instant of time. After all possible instantaneous values have been obtained, the total voltage waveform is drawn by connecting together these instantaneous values.

Combining OUT-OF-PHASE *Voltages*

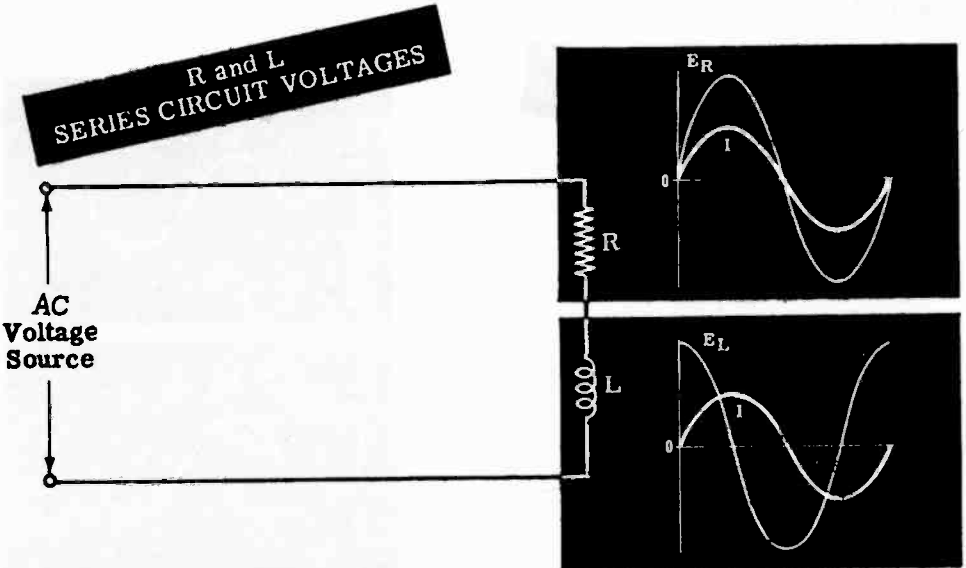


Combined instantaneous values are the result of combining the instantaneous values of E_1 and E_2

When combining out-of-phase voltages, the maximum value of the total voltage waveform is always less than the sum of the maximum values of the individual voltages. Also, the phase angle (which is the angle between any two waveforms) of the total voltage wave differs from that of the individual voltages, and depends on the relative value and phase angles of the individual voltages.

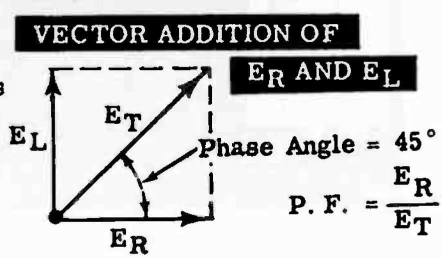
R and L Series Circuit Voltages

Suppose you consider an AC series circuit having negligible capacitance. The total circuit voltage depends on the voltage E_L across the circuit inductance and the voltage E_R across the circuit resistance. E_L leads the circuit current by 90 degrees while E_R is in phase with the circuit current; thus E_L leads E_R by 90 degrees.



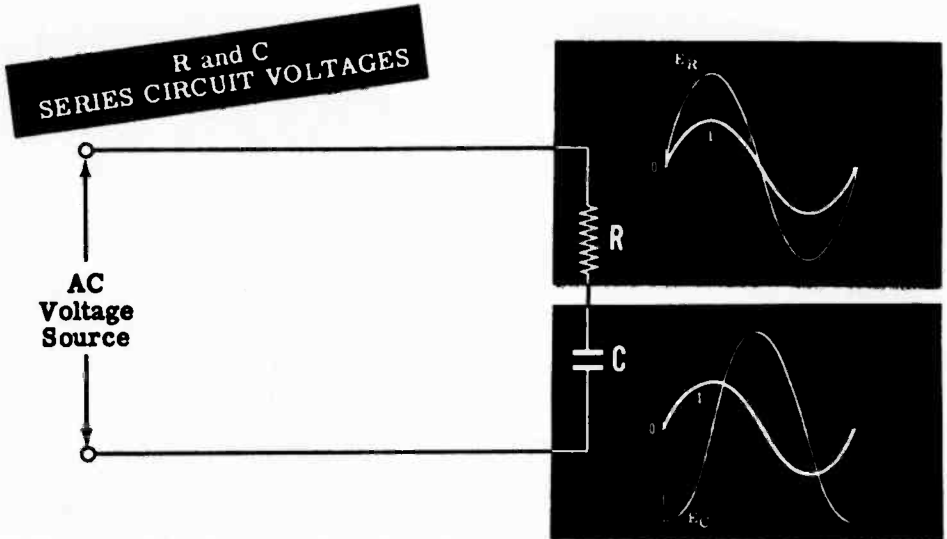
To add the voltages E_L and E_R, you can draw the two waveforms to scale and combine instantaneous values to plot the total voltage waveform. The total voltage waveform, E_T, then shows both the value and phase angle of E_T.

The value and phase angle of E_T also may be found by drawing vectors to represent E_L and E_R, completing the parallelogram and drawing the diagonal which represents E_T. The angle between E_R and E_T is the phase angle between total circuit voltage, E_T, and the circuit current, I_T. Use protractor to find phase angle.



R and C Series Circuit Voltages

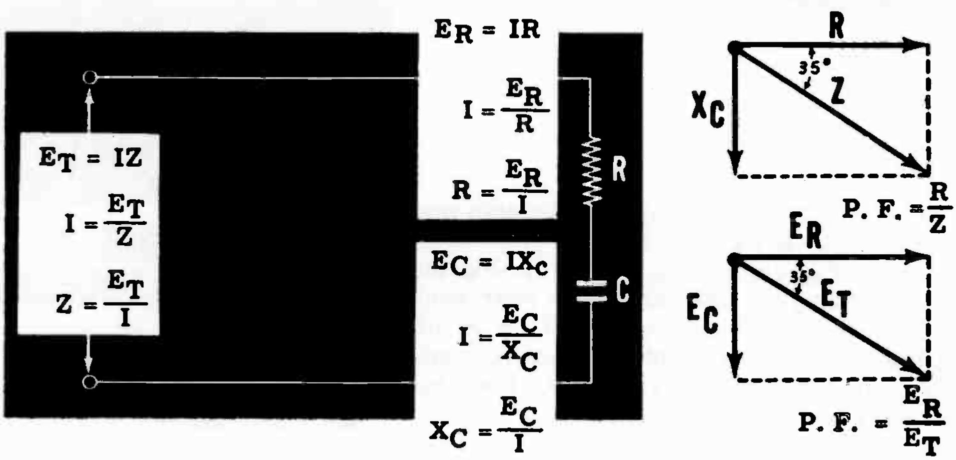
If your circuit consists of only R and C, the total voltage is found by combining E_R, the voltage across the resistance, and E_C, the voltage across the capacitance. E_R is in phase with the circuit current while E_C lags the circuit current by 90 degrees; thus E_C lags E_R by 90 degrees. The two voltages may be combined by drawing the waveforms to scale or by using vectors.



Voltage vectors for a series circuit are drawn in the same manner as resistance, reactance and impedance vectors. Following is an example of the use of Ohm's law, as it applies to each part and to the entire series circuit. Use a protractor to find the phase angle.

Ohm's Law

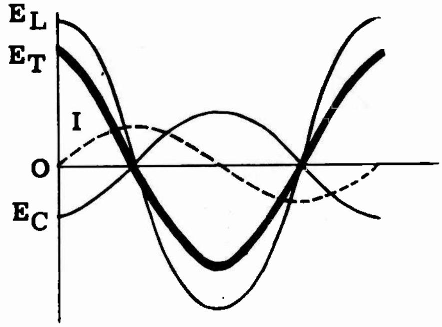
AND VECTOR RELATIONSHIP OF AN R AND C SERIES CIRCUIT



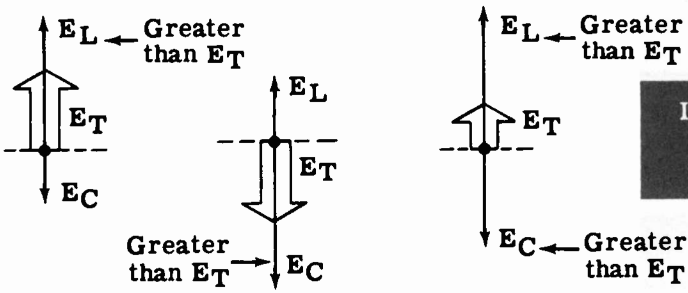
L and C Series Circuit Voltages

To find the total voltage of an L and C series circuit, you need only find the difference between E_L and E_C since they oppose each other directly. E_L leads the circuit current by 90 degrees while E_C lags it by 90 degrees. When the voltage waveforms are drawn, the total voltage is the difference between the two individual values and is in phase with the larger of the two voltages, E_L or E_C. For such circuits, the value of the total voltage can be found by subtracting the smaller voltage from the larger.

ADDITION OF E_L AND E_C TO FIND E_T



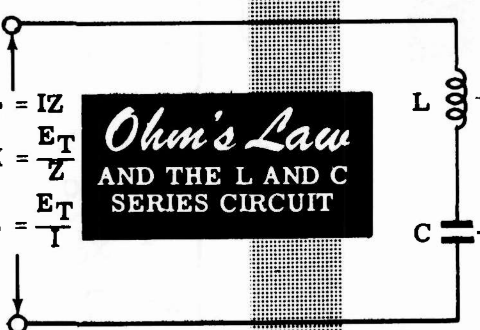
Either or both of the voltages E_L and E_C may be larger than the total circuit voltage in an AC series circuit consisting only of L and C.



Individual voltages are greater than the total voltages

The voltage vectors and reactance vectors for the L and C circuit are similar to each other, except for the units by which they are measured. Ohm's law applies to each part and to the total circuit as outlined below.

Ohm's Law AND THE L AND C SERIES CIRCUIT



$E_T = IZ$

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

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

$E_L = IX_L$

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

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

$E_C = IX_C$

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

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

A. P. = EI

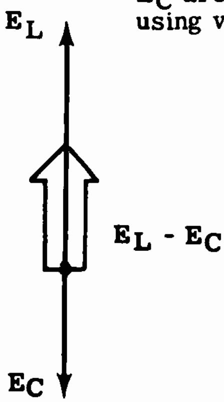
P. F. $= \frac{E_R}{E_T}$

T. P. = P. F. x A. P.

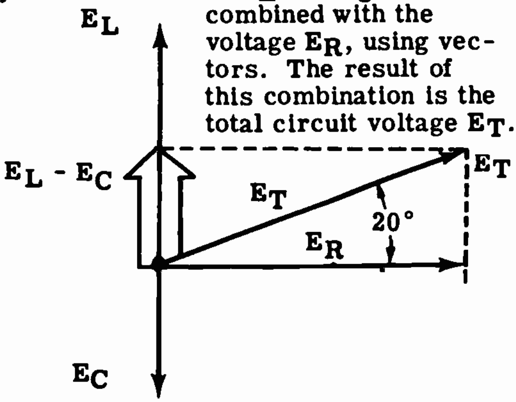
R, L and C Series Circuit Voltages

To combine the three voltages of an R, L and C series circuit by means of vectors, two steps are required:

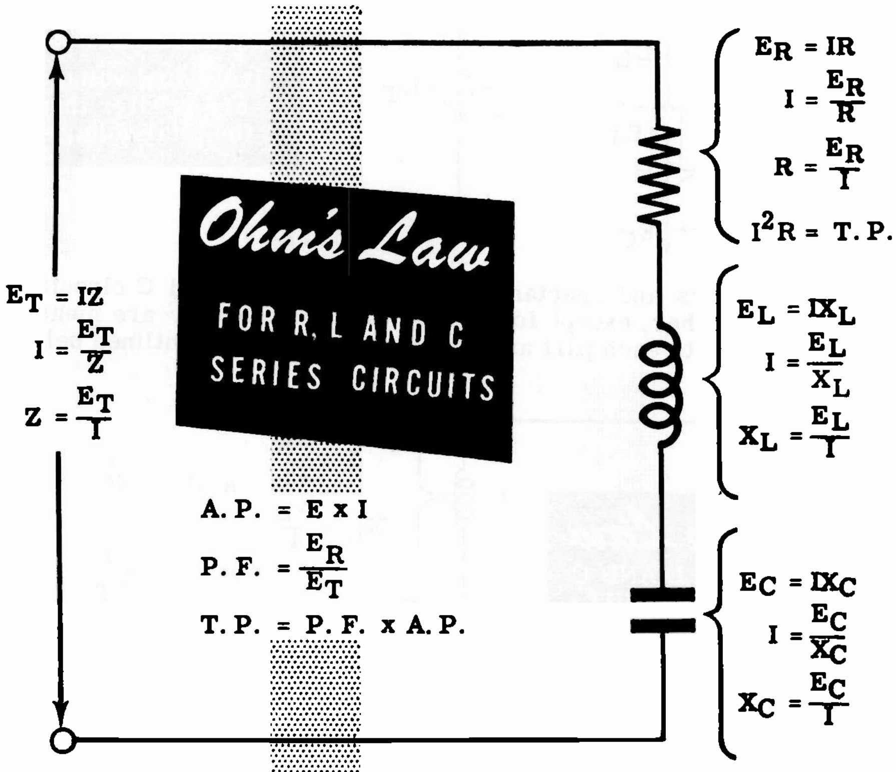
1. The voltages E_L and E_C are combined by using vectors.



2. The combined value of E_L and E_C is next combined with the voltage E_R, using vectors. The result of this combination is the total circuit voltage E_T.

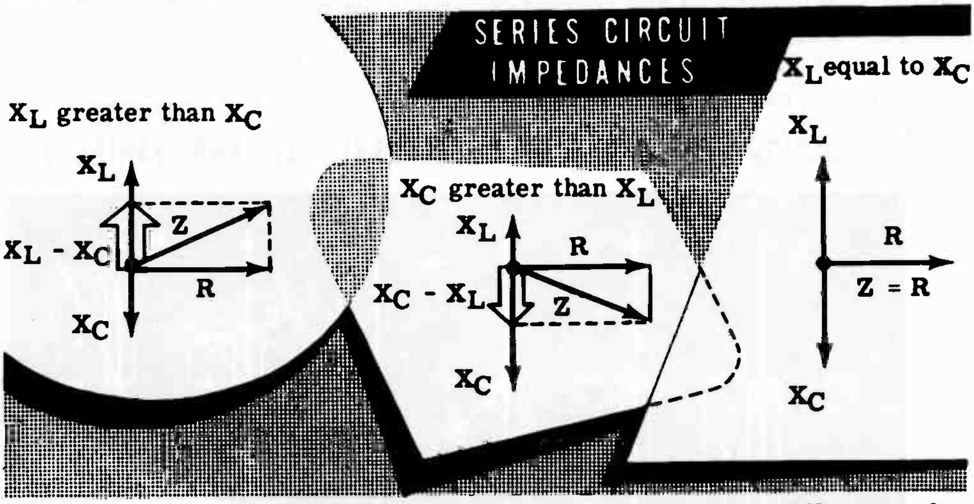


You can use Ohm's law for any part of the circuit by substituting X_L or X_C for R across inductors and capacitors respectively. Then, for the total circuit, Z replaces R as it is used in the original formula.



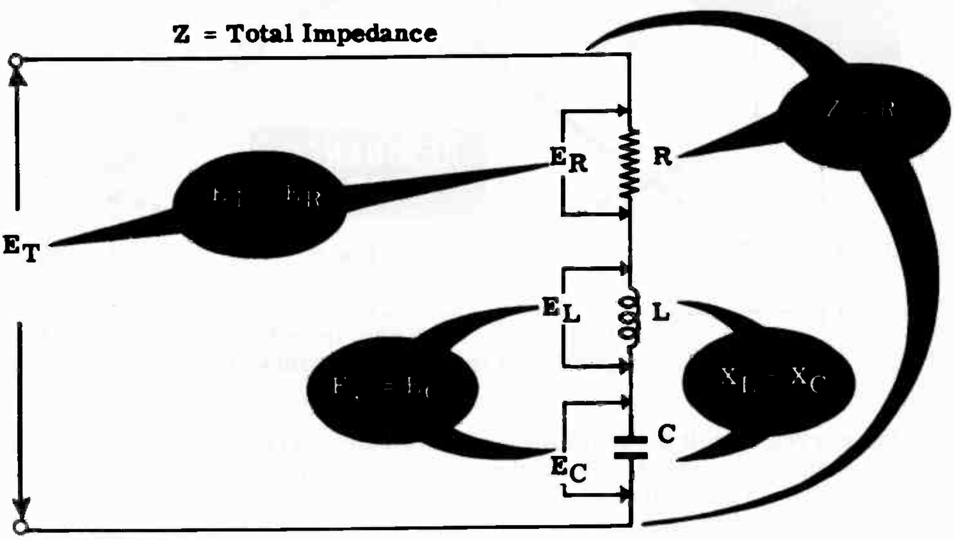
Series Circuit Resonance

In any series circuit containing both L and C, the circuit current is greatest when the inductive reactance X_L equals the capacitive reactance X_C, since under those conditions the impedance is equal to R. Whenever X_L and X_C are unequal, the impedance Z is the diagonal of a vector combination of R and the difference between X_L and X_C. This diagonal is always greater than R, as shown below. When X_L and X_C are equal, Z is equal to R and is at its minimum value, allowing the greatest amount of circuit current to flow.



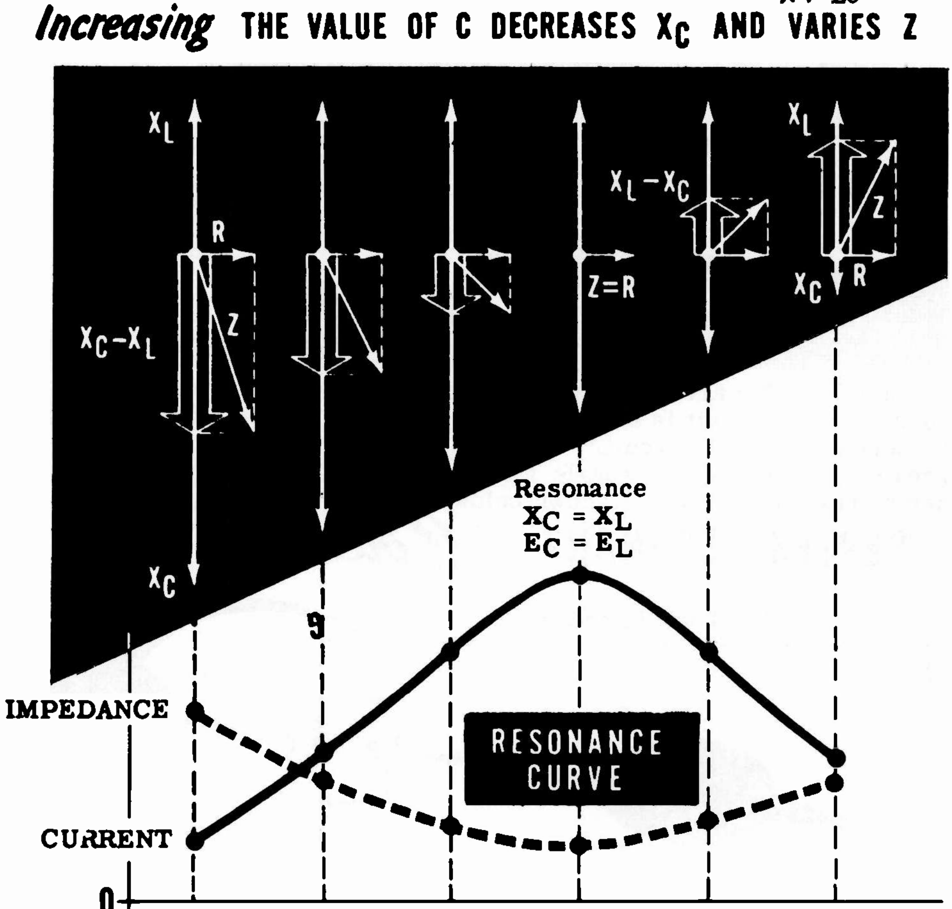
When X_L and X_C are equal the voltages across them, E_L and E_C, are also equal and the circuit is said to be "at resonance." Such a circuit is called a "series resonant circuit." Both E_L and E_C, although equal, may be greater than E_T which equals E_R. The application of Ohm's law to the series resonant circuit is shown below.

SERIES RESONANT *Circuit*



Series Circuit Resonance (continued)

If either the frequency, the inductive reactance or the capacitive reactance is varied in a series circuit consisting of R, L and C, with the other values kept constant, the circuit current variation forms a curve called the "resonance curve." This curve shows the rise in current to a maximum value at exact resonance, and the decrease in current on either side of resonance. For example, consider a 60-cycle AC series circuit having a fixed value of inductance and a variable value of capacitance, as in a radio receiver. The circuit impedance and current variations, as the capacitance is changed, are shown below in outline form. At resonance $X_L = X_C$, $E_L = E_C$, $E_T = E_R$, Z is at its minimum value and I_T is at its maximum value. Resonant frequency (f_r) is calculated by the formula $f_r = \frac{1}{2\pi\sqrt{LC}}$



Effect on current and impedance of varying the capacitance through resonance in a series circuit.

Similar curves result if capacitance and frequency are held constant while the inductance is varied, and if the inductance and capacitance are held constant while the frequency is varied.

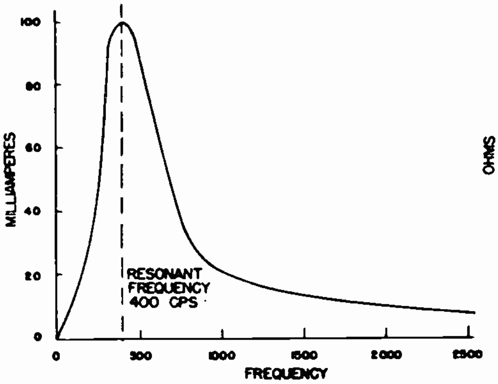
Series Circuits Resonance (continued)

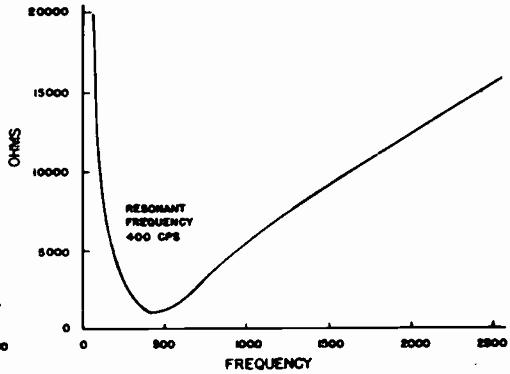
The example described on the previous sheet may be discussed with the emphasis placed on a varying frequency of the input voltage and with the inductance and capacitance held constant.

Variation of the voltage input frequency to an R, L, and C circuit (over a suitable range) results in an output current curve which is similar to the resonance curve on the previous sheet. When operated below the resonant frequency the current output is low and the circuit impedance is high. Above resonance the same condition occurs. At the resonant frequency the output current curve is at its peak and the impedance curve is at a minimum. The graphs of current and impedance below are typical of an R, L, C series circuit when only the input signal frequency is varied.

CURRENT THROUGH A SERIES RESONANT CIRCUIT IS MUCH HIGHER AT THE RESONANT FREQUENCY THAN AT ANY OTHER FREQUENCY

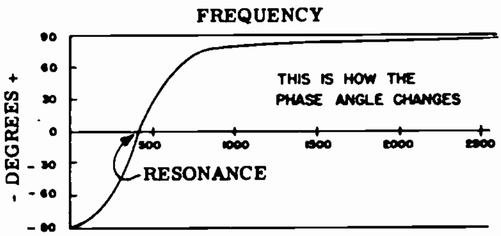
THIS GRAPH SHOWS HOW THE SERIES IMPEDANCE OF THE CIRCUIT VARIES WITH FREQUENCY





Further light as to the effects of reactance below and above resonance can be seen by looking at the phase angle graph below. The phase angle is clearly capacitive (negative) below resonance, and is clearly inductive (positive) above resonance. The phase angle is, of course, zero at the exact frequency of resonance.

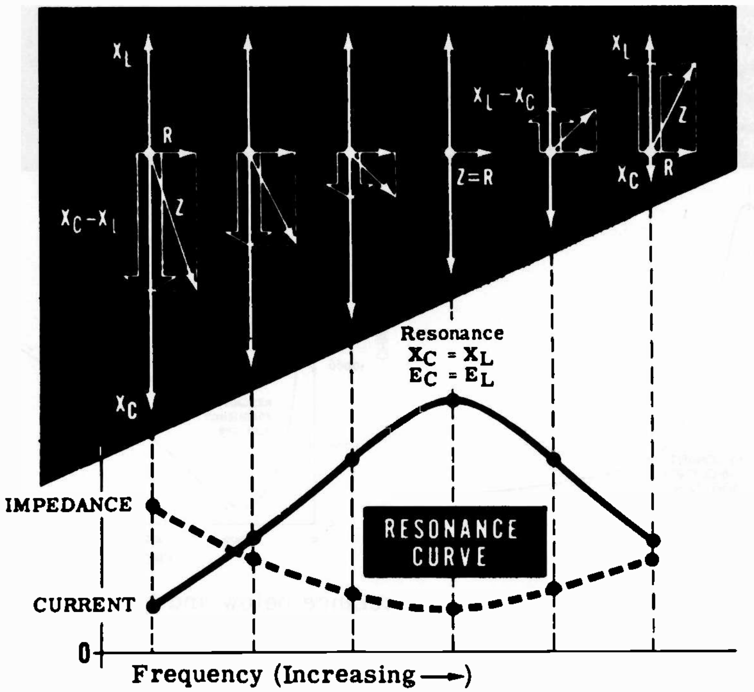
PHASE ANGLE GRAPH



Power at Resonance in Series Circuits

You have already learned that in AC circuits the power is equal to the product of the volts and amperes only when the current and voltage are in phase. If the voltage and current are not in phase the power expended will be something less than the product of E and I. The amount by which the expended power is less than the apparent power (the E times I) is determined by the power factor of the circuit. This power factor is essentially the ratio of the resistance divided by the impedance of the circuit. It is often called the cosine of the phase angle (cos θ) which is formed by the R and Z in an impedance triangle.

In a series circuit consisting of inductance, resistance, and capacitance the condition of resonance occurs when the inductive reactance and the capacitive reactance are numerically equal and therefore completely cancel each other; see the diagram below.



Since X_L is equal to X_C and since they oppose and therefore cancel each other out, the total impedance of the circuit (Z) must be equal to the resistance (R). Further, the phase angle θ does not exist and is therefore considered to be equal to zero.

If the impedance is equal to R then the power factor must be equal to 1, as follows:

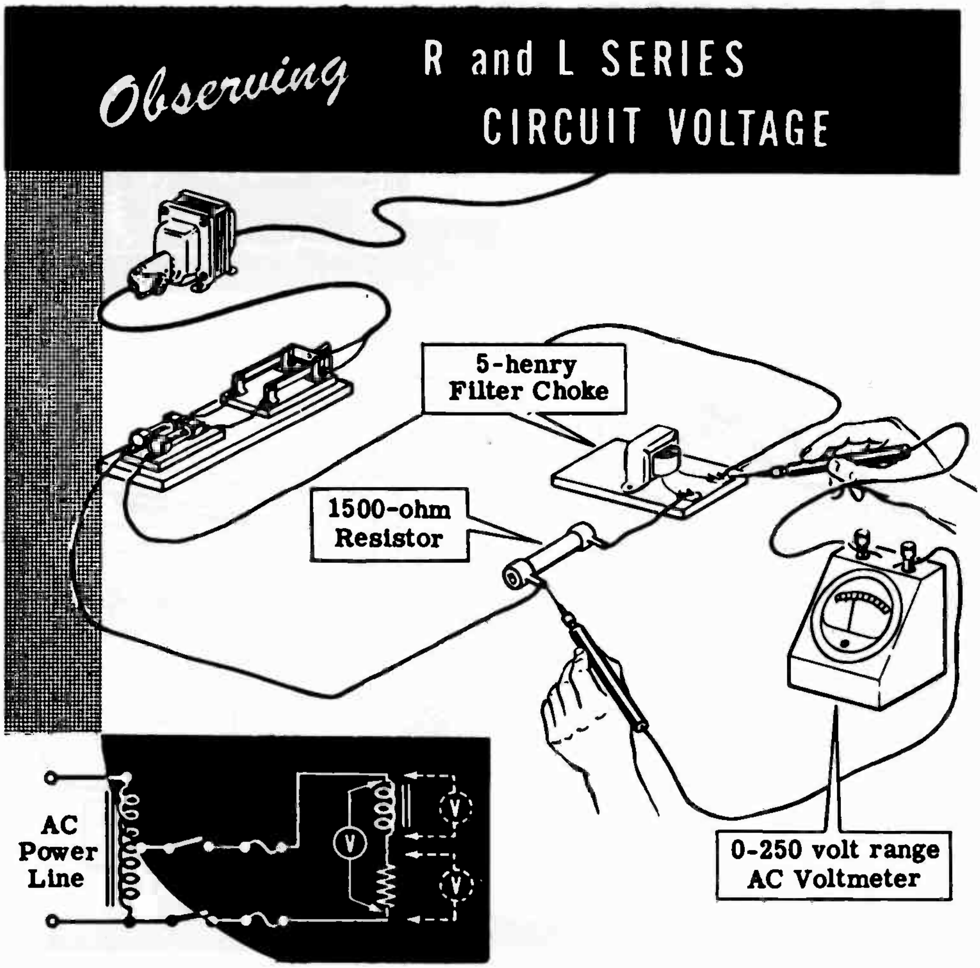
$$Z = R$$

and

$$\cos \theta = \frac{R}{Z} = \frac{R}{R} = 1$$

Demonstration—R and L Series Circuit Voltage

To demonstrate the relationship of the various voltages in an R and L series circuit, the instructor connects a 1500-ohm resistor and a 5-henry filter choke to form an L and R series circuit. With the switch closed, individual voltage readings are taken across the choke and the resistor. Also, the total voltage across the series combination of the resistor and choke is measured. Notice that, if the measured voltages across the choke and resistor are added directly, the result is greater than the total voltage measured across the two in series.

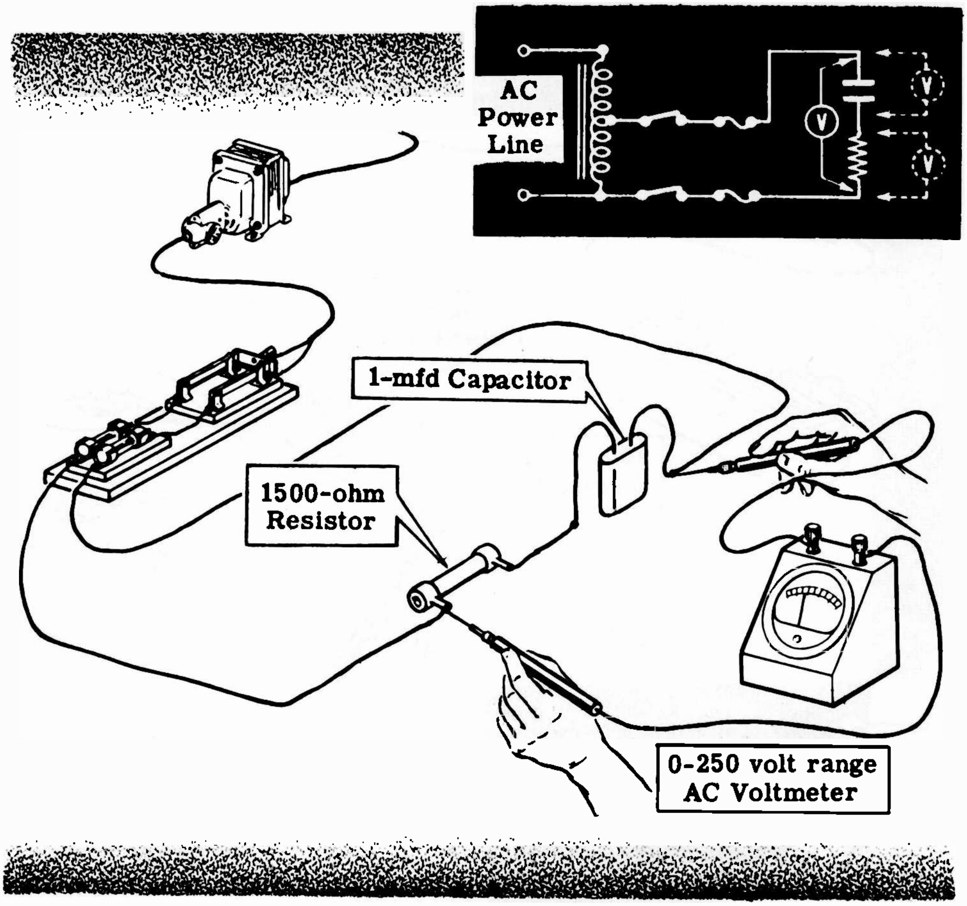


The voltage E_L measured across the 5-henry filter choke is approximately 47.5 volts, and E_R measured across the 1500-ohm resistor is about 37.5 volts. When added directly, the voltages E_L and E_R total approximately 85 volts but the actual measured voltage across the resistor and filter choke in series is only about 60 volts. Using vectors to combine E_R and E_L, you see that the result is about 60 volts—the actual total circuit voltage as measured.

Demonstration—R and C Series Circuit Voltage

Next the instructor removes the 5-henry filter choke from the circuit, replaces it with a 1-mfd capacitor and measures the individual and total voltages of the circuit. Again you see that the sum of the voltages across the capacitor and resistor is greater than the actual measured total voltage.

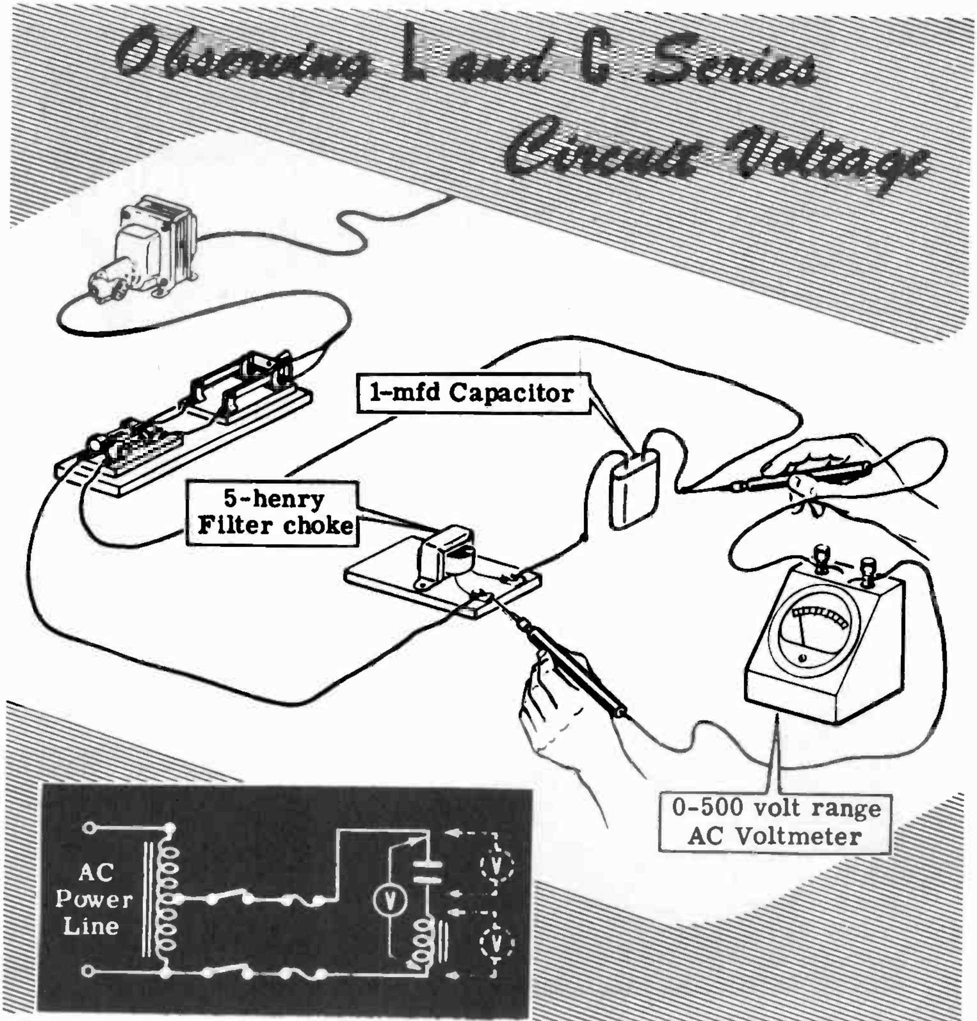
Measuring the Voltage of an R and C SERIES CIRCUIT....



The measured voltage across the capacitor is about 53 volts, while that across the resistor is approximately 30 volts. When added these voltages total 83 volts, but the actual measured voltage across the capacitor and resistor in series is only approximately 60 volts. Using vectors to combine the two circuit voltages, E_R and E_C, you see that the result is about 60 volts, equal to the measured voltage of the circuit. Notice that, whenever the circuit power is removed, the instructor shorts the terminals of the capacitor together to discharge it.

Demonstration—L and C Series Circuit Voltages

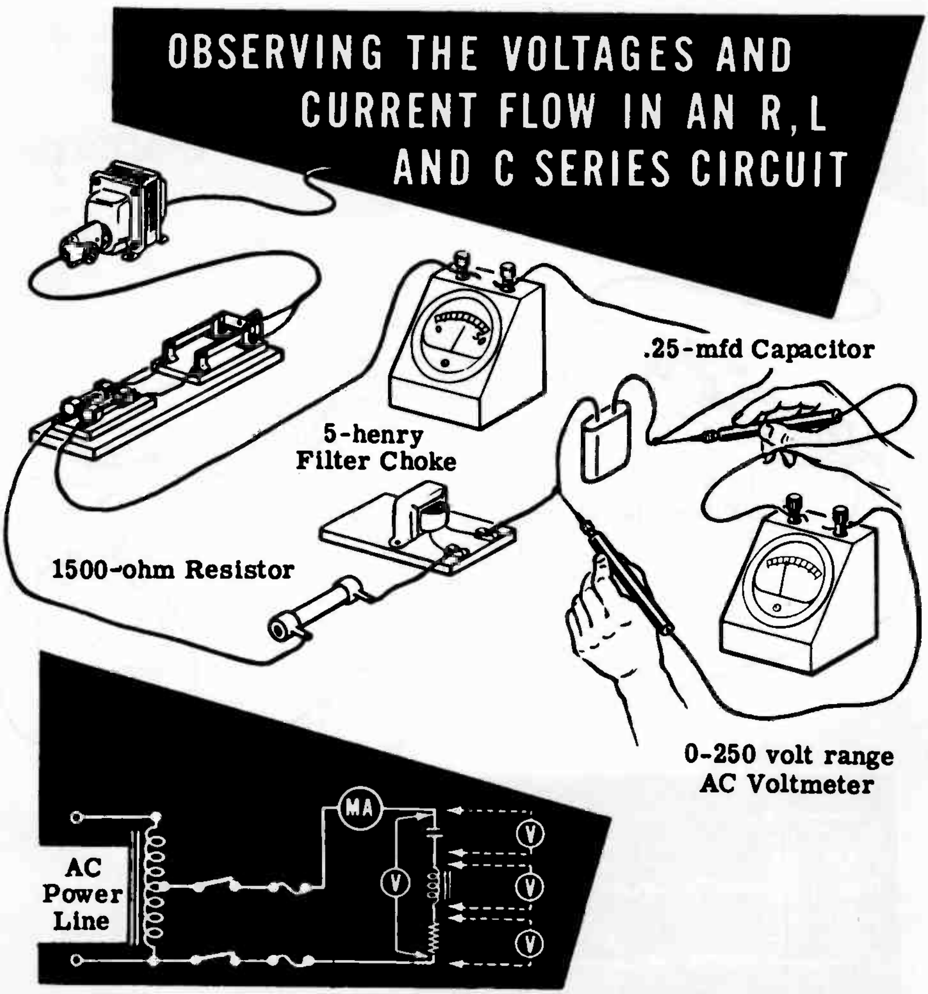
By replacing the 1500-ohm resistor with a 5-henry filter choke, the instructor forms an L and C series circuit having negligible resistance. With the power applied, the voltages across the filter choke and capacitor are measured individually and the total voltage is measured across the series circuit. Notice that the voltage across the inductance (filter choke) alone is greater than the measured total voltage across the circuit. Adding the voltage across the filter choke to that across the capacitor results in a much greater value than the actual measured total circuit voltage.



Using vectors to combine the two voltages, you see that the result is approximately equal to the measured total voltage, or about 60 volts. Although it is considered negligible, the resistance of the filter choke wire causes a slight difference in the computed and actual results. A 0-500 volt range AC meter is used instead of the 0-250 volt range meter, as the readings may exceed the 0-250 volt scale.

Demonstration—Series Resonance

To demonstrate series resonance, the instructor replaces the 1-mfd capacitor with a 0.25-mfd capacitor and inserts a 1500-ohm, 10-watt resistor in series with the 5-henry filter choke and the capacitor. This forms an R, L and C series circuit in which C will be varied to show the effect or resonance on circuit voltage and current. A 0-50 ma. AC milliammeter is connected in series with the circuit to measure the circuit current. A 0-250 volt range AC voltmeter will be used to measure circuit voltages.

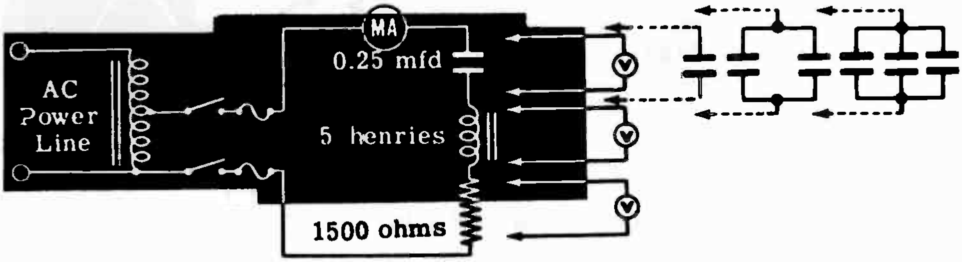


With the switch closed, you see that the current is not large enough to be read accurately since it is less than 10 ma. As the instructor measures the various circuit voltages, you see that the voltage E_R across the resistor is less than 10 volts, the voltage E_L across the filter choke is about 13 volts and the voltage E_C across the capacitor is about 55 volts. The total voltage E_T across the entire circuit is approximately 60 volts.

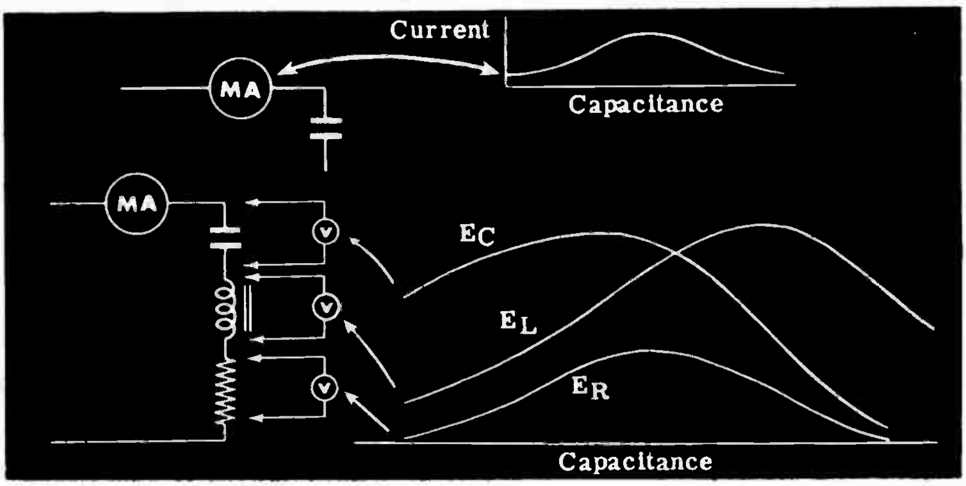
Demonstration—Series Resonance (continued)

By using various parallel combinations of the 0.25-mfd, 0.5-mfd, 1-mfd and 2-mfd capacitors, the instructor varies the circuit capacitance from 0.25 mfd to 3.5 mfd in steps of 0.25 mfd. Notice that he removes the circuit power and discharges all capacitors used before removing or adding capacitors to the circuit. You see that as the capacitance is increased the current rises to a maximum value reached at the point of resonance, then decreases as the capacitance is increased further.

OBSERVING THE CIRCUIT VOLTAGES AND CURRENT CHANGE AS THE CAPACITANCE VALUE IS CHANGED



Except for the total circuit voltage E_T, the measured circuit voltages vary as the capacitance is changed. The voltage E_R across the resistor changes in the same manner as the circuit current. For capacitance values less than the resonance value, E_C is greater than E_L. Both voltages increase as the capacitance approaches the resonance point, with E_L increasing more rapidly so that at resonance E_L equals E_C. As the capacitance is increased beyond the resonance point, both E_C and E_L decrease in value. E_C decreases more rapidly, so that E_L is greater than E_C when the circuit capacitance is greater than the value required for resonance. (The maximum E_L and E_C are not equal due to the relatively high resistance. If the resistance is reduced, E_L and E_C will be equal at resonance.)

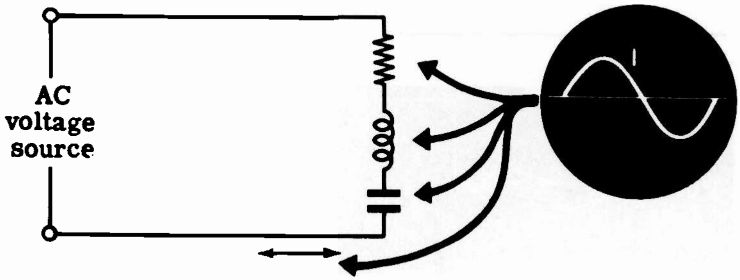


CURRENT, VOLTAGE AND RESONANCE IN AC SERIES CIRCUITS

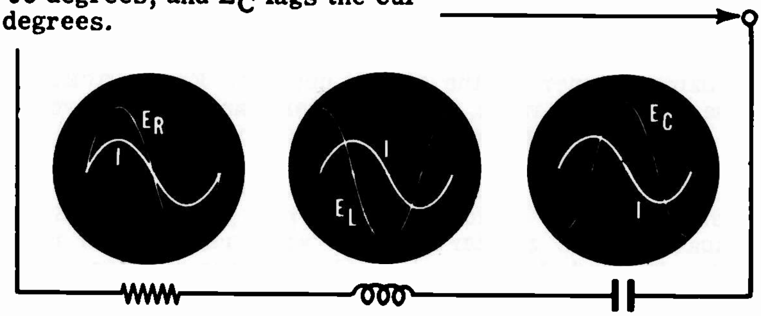
Review of AC Series Circuit Voltages and Current

You have found that the rules for AC series circuit voltage and current are the same as those for DC circuits, except that the various circuit voltages must be added by means of vectors because of the phase difference between the individual voltages. Now review what you have found out about AC series circuit current, voltages and resonance, and how Ohm's law applies to an AC series circuit.

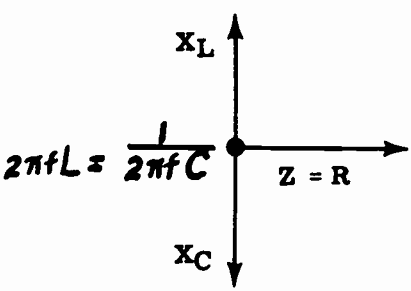
AC SERIES CIRCUIT CURRENT — The current is the same in all parts of a series circuit.

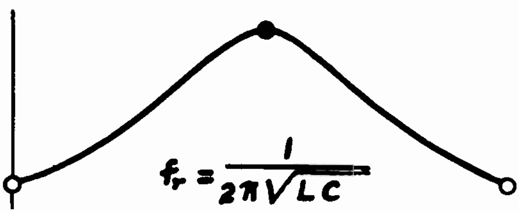


AC SERIES CIRCUIT VOLTAGES — E_R is in phase with the current, E_L leads the current by 90 degrees, and E_C lags the current by 90 degrees.

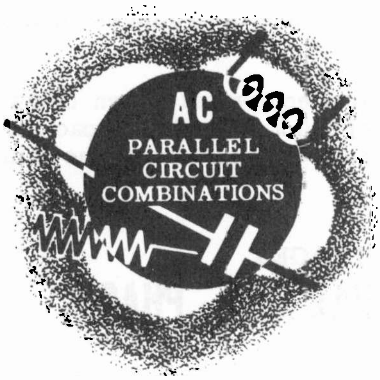


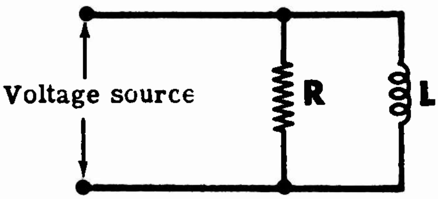
SERIES CIRCUIT RESONANCE — At resonance $X_L = X_C$, $E_L = E_C$, current is maximum and $Z = R$. P. F. = 100%.

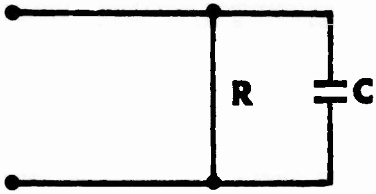




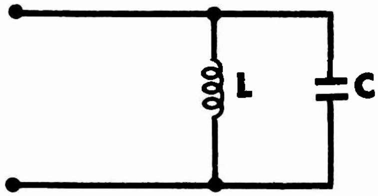
AC Parallel Circuit Combinations



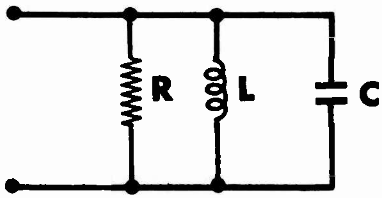




Electrical equipment is usually connected in parallel across AC power lines, forming parallel combinations of R, L and C. As in series circuits, every parallel circuit contains a certain amount of resistance, inductive reactance and capacitive reactance; but for a given circuit any of these factors may be so negligible that it can be disregarded.



The same combinations of R, L and C which are used to form the various types of series circuits may also be used to form parallel circuits. If one factor is negligible, the three possible combinations are R and L, R and C, or L and C, while a fourth type of parallel circuit contains R, L and C.

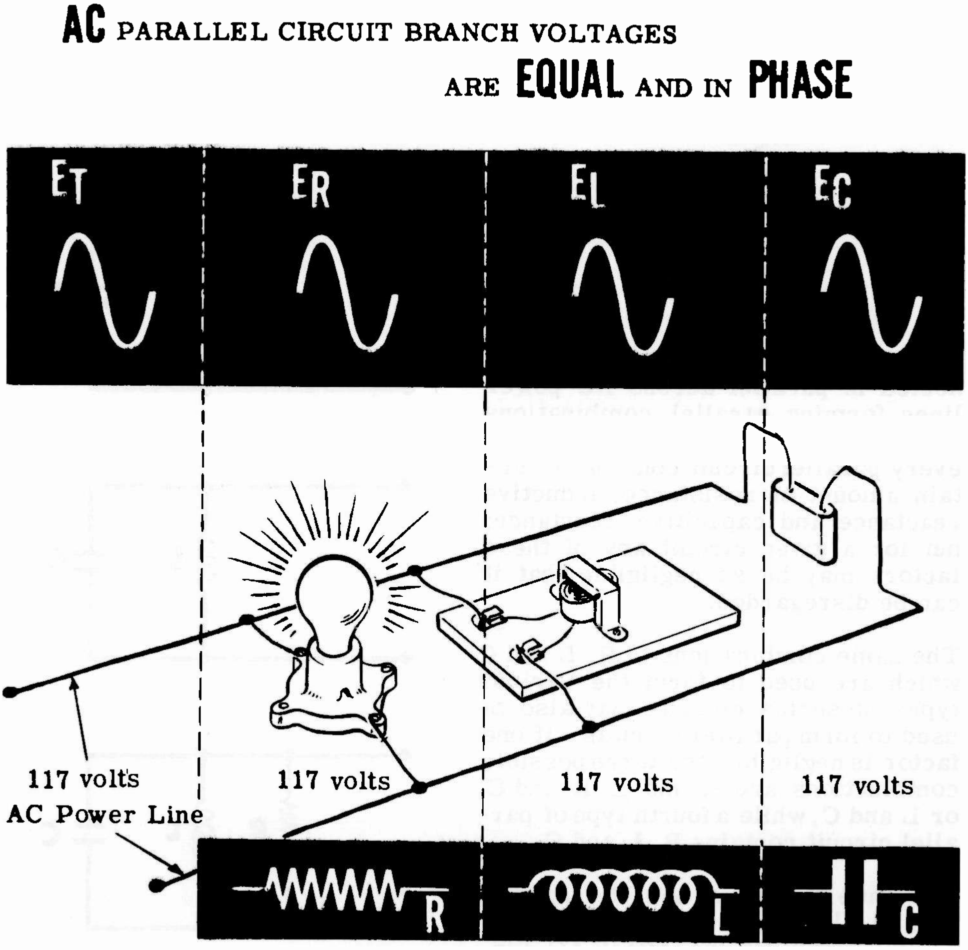


You have found out how R, L and C, individually and in various series circuit combinations, affect AC current flow, voltage, phase angle and power. Now you will find out how current, voltage, phase angle and power are affected by the various parallel combinations.

Voltages in AC Parallel Circuits

You will remember that in a parallel DC circuit the voltage across each of the parallel branches is equal. This is also true of AC parallel circuits; the voltages across each parallel branch are equal and also equal E_T, the total voltage of the parallel circuit. Not only are the voltages equal, but they are also in phase.

For example, if the various types of electrical equipment shown below—a lamp (resistance), a filter choke (inductance) and a capacitor (capacitance) —are connected in parallel, the voltage across each is exactly the same.

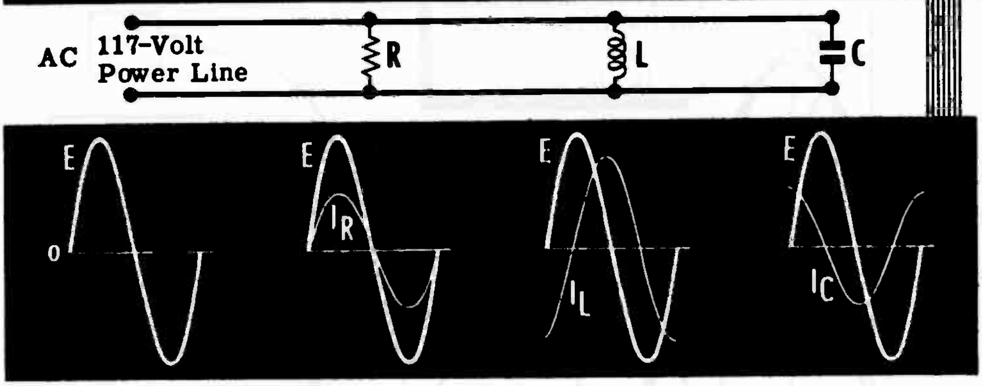


Regardless of the number of parallel branches, the value of the voltage across them is equal and in phase. All of the connections to one side of a parallel combination are considered to be one electrical point, as long as the resistance of the connecting wire may be neglected.

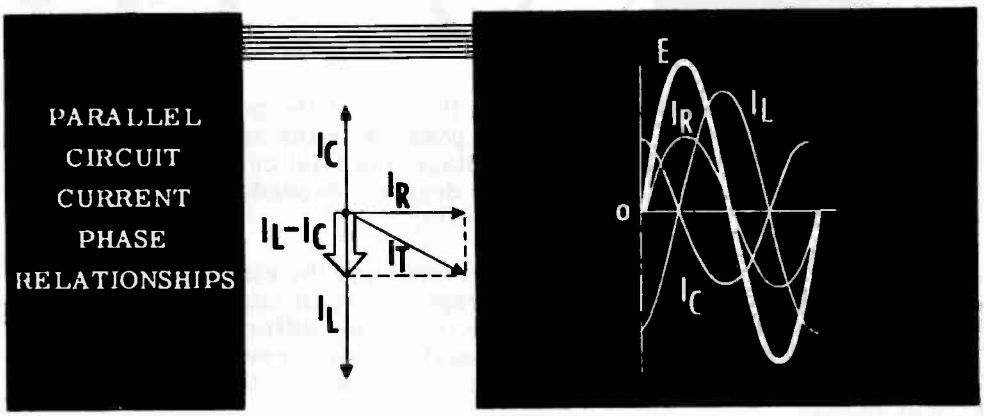
Currents in AC Parallel Circuits

The current flow through each individual branch is determined by the opposition offered by that branch. If your circuit consists of three branches —one a resistor, another an inductor and the third a capacitor—the current through each branch depends on the resistance or reactance of that branch. The resistor branch current I_R is in phase with the circuit voltage E_T, while the inductor branch current I_L lags the circuit voltage by 90 degrees and the capacitor branch current I_C leads the voltage by 90 degrees.

AC PARALLEL CIRCUIT CURRENTS

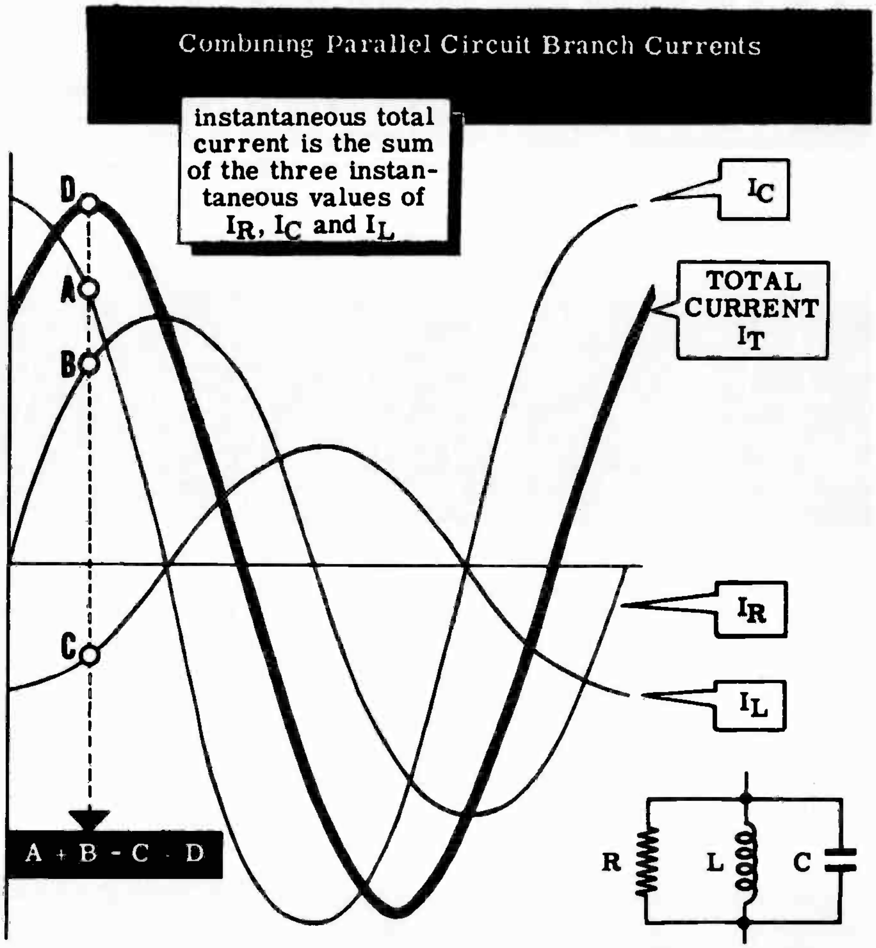


Because of the phase difference between the branch currents of an AC parallel circuit, the total current I_T cannot be found by adding the various branch currents directly—as it can for a DC parallel circuit. When the waveforms for the various circuit currents are drawn in relation to the common circuit voltage waveform, X_L and X_C again are seen to cancel each other since the waveforms for I_L and I_C are exactly opposite in polarity at all points. The resistance branch current I_R, however, is 90 degrees out of phase with both I_L and I_C and, to determine the total current flow by using vectors, I_R must be combined with the difference between I_L and I_C.


PARALLEL CIRCUIT CURRENT PHASE RELATIONSHIPS

Currents in AC Parallel Circuits (continued)

To add the branch currents in an AC parallel circuit, the instantaneous values of current are combined, as voltages are in a series circuit, to obtain the instantaneous values of the total current waveform. After all the possible instantaneous values of current are obtained, the total current waveform is drawn by connecting together the instantaneous values.



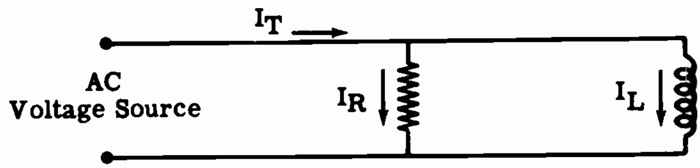
The maximum value of I_T is less than the sum of the maximum values of the individual currents, and is out of phase with the various branch currents. With respect to the circuit voltage, the total current either <u>leads</u> or <u>lags</u> I_C and I_L between zero and 90 degrees, depending on whether the inductive or capacitive reactance is greater.

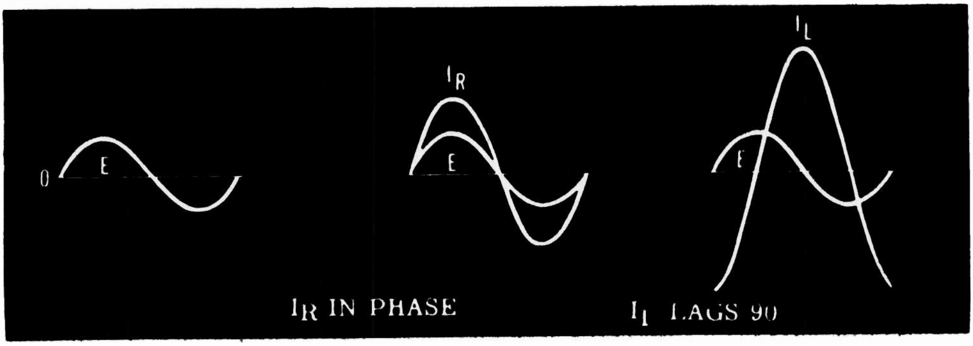
A graph showing the various circuit currents and the circuit voltage of an AC parallel circuit is similar to the graph of circuit current and voltages for an AC series circuit. They differ in that the different series circuit voltages are drawn with reference to total circuit current, while for parallel circuits the different currents are drawn with reference to the total circuit voltage.

R and L Parallel Circuit Currents

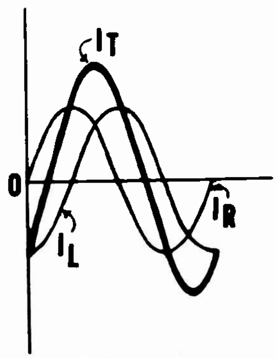
If your AC parallel circuit consists of a resistance and inductance connected in parallel, and the circuit capacitance is negligible, the total circuit current is a combination of I_R (the current through the resistance) and I_L (the current through the inductance). I_R is in phase with the circuit voltage E_T while I_L lags the voltage by 90 degrees.

PHASE RELATIONSHIPS IN AN R AND L PARALLEL CIRCUIT

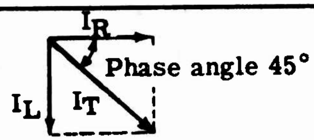




To find the total current I_T, you can draw I_R and I_L to scale and in the proper phase relationship to each other and combine the corresponding instantaneous values to plot the total current waveform. This waveform then shows both the maximum value and the phase angle of I_T.



VECTOR ADDITION OF I_R AND I_L



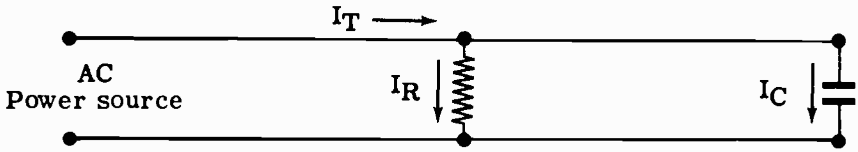
COMBINING WAVEFORMS I_R AND I_L

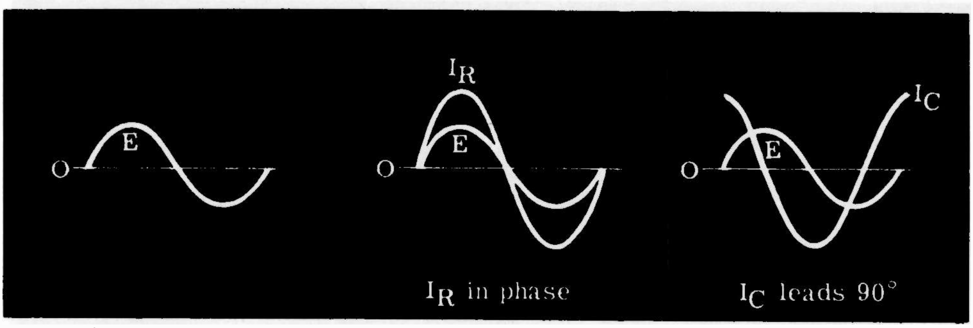
You can also use an easier method to find the value and phase angle of I_T. By drawing vectors to scale representing I_R and I_L, then combining the vectors by completing the parallelogram and drawing the diagonal, you can obtain both the value and phase angle of I_T. The length of the diagonal represents the value of I_T, while the angle between I_T and I_R is the phase angle between total circuit voltage, E_T, and the total circuit current, I_T.

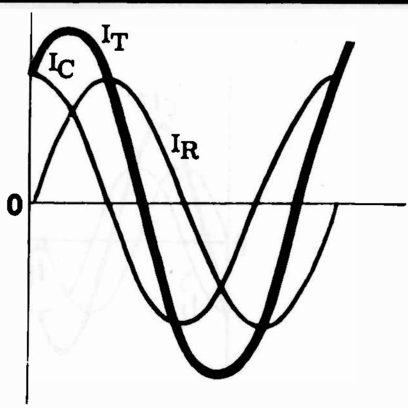
R and C Parallel Circuit Currents

The total current of an AC parallel circuit which consists only of R and C is found by combining I_R (the resistance current) and I_C (the capacitance current). I_R is in phase with the circuit voltage E_T, while I_C leads the voltage by 90 degrees. To find the total current and its phase angle when I_R and I_C are known, you can draw the waveforms of I_R and I_C or their vectors.

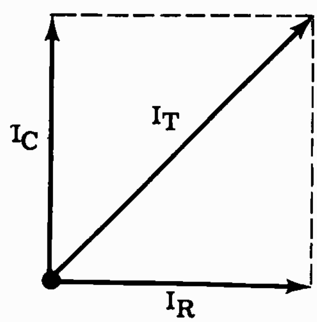
FINDING THE TOTAL CURRENT IN AN R AND C CIRCUIT. . .







Combining I_R and I_C Waveforms



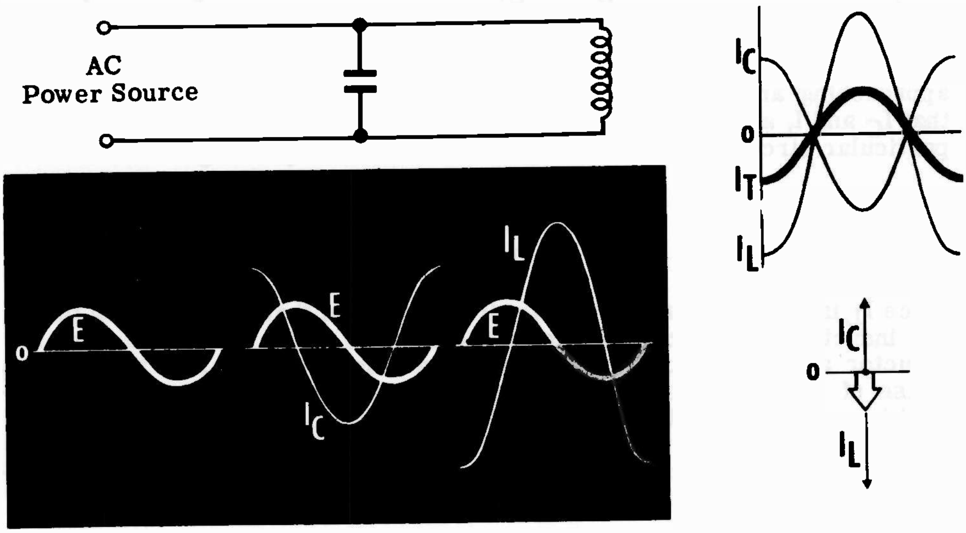
Adding I_R and I_C Vectors

While the capacitance does increase the circuit current, only the resistance current consumes power, so that parallel circuits containing a capacitance branch will pass more current than is necessary to provide a given amount of power. This means that the power line wires which carry current to such circuits must be larger than if the circuit were purely resistive.

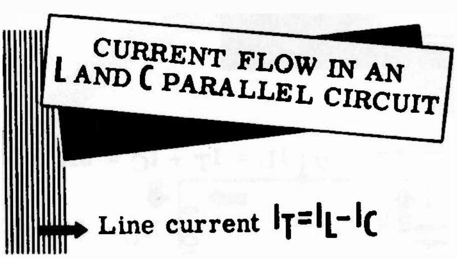
L and C Parallel Circuit Currents

When your parallel circuit consists only of L and C, the total current is equal to the difference between I_L and I_C since they are exactly opposite in phase relationship. When the waveforms for I_L and I_C are drawn, you see that all the instantaneous values of I_L and I_C are of opposite polarity. If all the corresponding combined instantaneous values are plotted to form the waveform of I_T, the maximum value of this waveform is equal to the difference between I_L and I_C. For such circuits the total current can be found by subtracting the smaller current, I_L or I_C, from the larger.

FINDING THE TOTAL CURRENT IN AN L AND C PARALLEL CIRCUIT



The relationships and paths of circuit currents for L and C circuits are shown below.



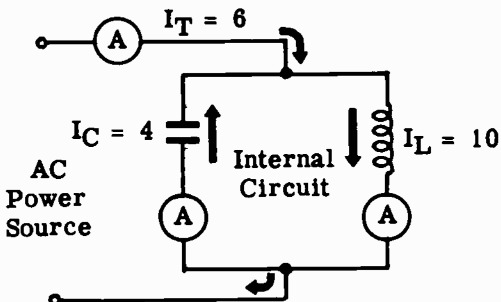


Diagram of circuit showing circulating current

The parallel circuit can also be considered as consisting of an internal and external circuit. Since the current flowing through the inductance is exactly opposite in polarity to that which is flowing through the capacitance at the same time, an internal circuit is formed. The amount of current flow around this internal circuit is equal to the smaller of the two currents, I_L and I_C. The amount of current flowing through the external circuit (the voltage source) is equal to the difference between I_L and I_C.

L and C Parallel Circuit Currents (continued)

The relationship between the various currents in a parallel circuit consisting of L and C is illustrated in the following example. A capacitor and an inductor are connected in parallel across a 60-cycle, 150-volt source, so that $X_L = 50$ ohms and $X_C = 75$ ohms. The currents in the circuit are:

$$I_L = \frac{E}{X_L} = \frac{150}{50} = 3A. \qquad I_C = \frac{E}{X_C} = \frac{150}{75} = 2A.$$

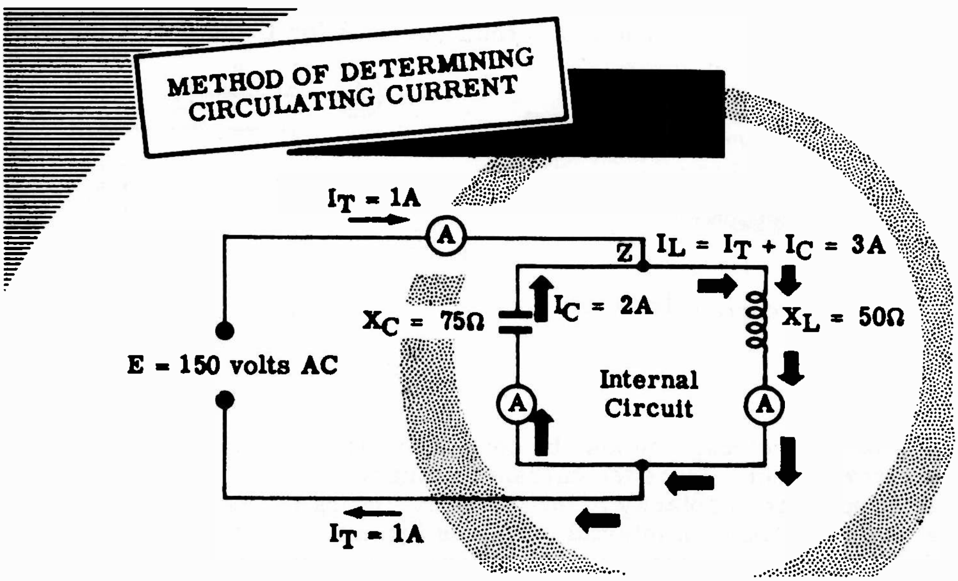
Since I_L and I_C are exactly opposite in phase, they have a canceling effect on each other. Therefore, the total current $I_t = I_L - 3 - 2 = 1A$. Due to the phase relationship of I_L and I_C, the current flow through the capacitor is always opposite in direction to the current flow through the inductor.

Using this phase relationship and the Kirchhoff's law relating to currents approaching and leaving a point in a circuit, you can see in the diagram that I_C and I_t are approaching point A while I_L is leaving point A. For this particular circuit, I_L must be equal to the sum of I_t and I_C.

$$I_L = I_t + I_C$$
$$3 = 1 + 2$$

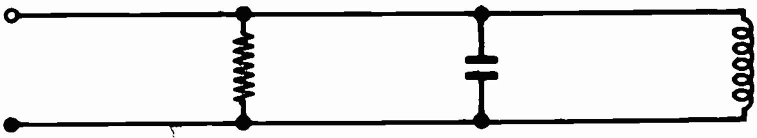
Since I_L is made up partially of I_C, it can be seen that I_C must flow through the inductor. Therefore, I_C flows through the capacitor and through the inductor and then back through the capacitor. The result of the opposing phase of I_L and I_C is to form an internal circuit, whose circulating current has a value equal to the smaller of I_L and I_C, in this case I_C.

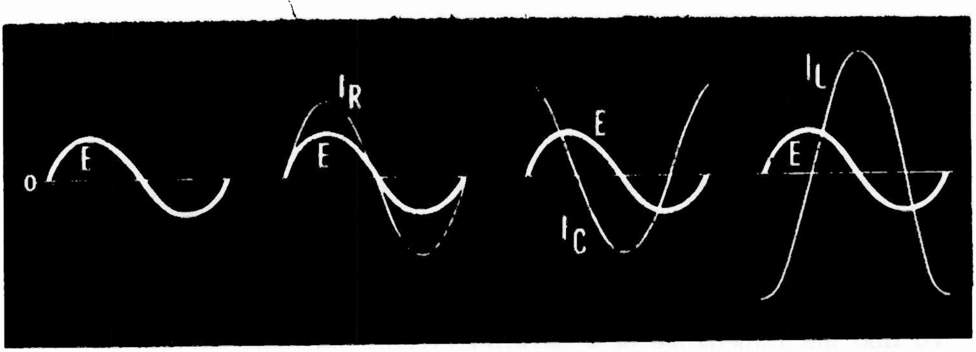
If the values of X_L and X_C were reversed, I_L would be the circulating current. The smaller current (I_L or I_C) is always the circulating current.



R, L and C Parallel Circuit Currents

FIND THE TOTAL CURRENT IN A R, L AND C PARALLEL CIRCUIT

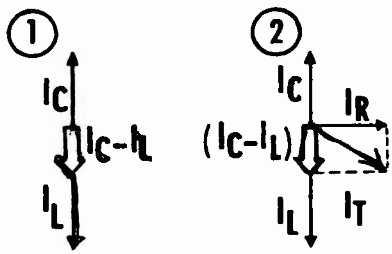




To combine the three branch currents of an R, L and C alternating-current parallel circuit by means of vectors requires two steps as outlined below:

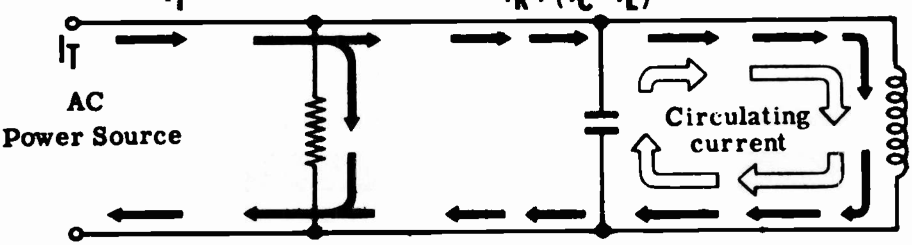
1. The currents I_L and I_C are combined by using vectors. (Both the value, which may be obtained by direct subtraction, and the phase angle of this combined current are required.)

2. The combined value of I_L and I_C is then combined with I_R to obtain the total current.



In an R, L and C circuit—as in the L and C circuit—a circulating current equal to the smaller of the two currents I_L and I_C flows through an internal circuit consisting of the inductance branch and the capacitance branch. The total current which flows through the external circuit (the voltage source) is the combination of I_R and the difference between the currents I_L and I_C.

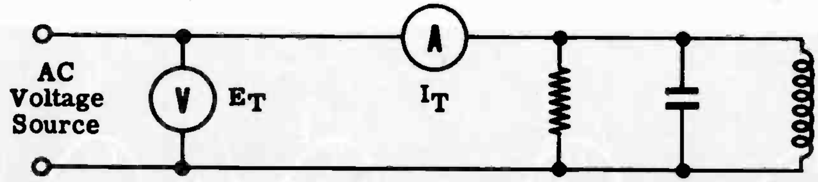
I_T = Vector addition of $I_R+(I_C-I_L)$



Current Flow in R, L and C Parallel Circuit

AC Parallel Circuit Impedance

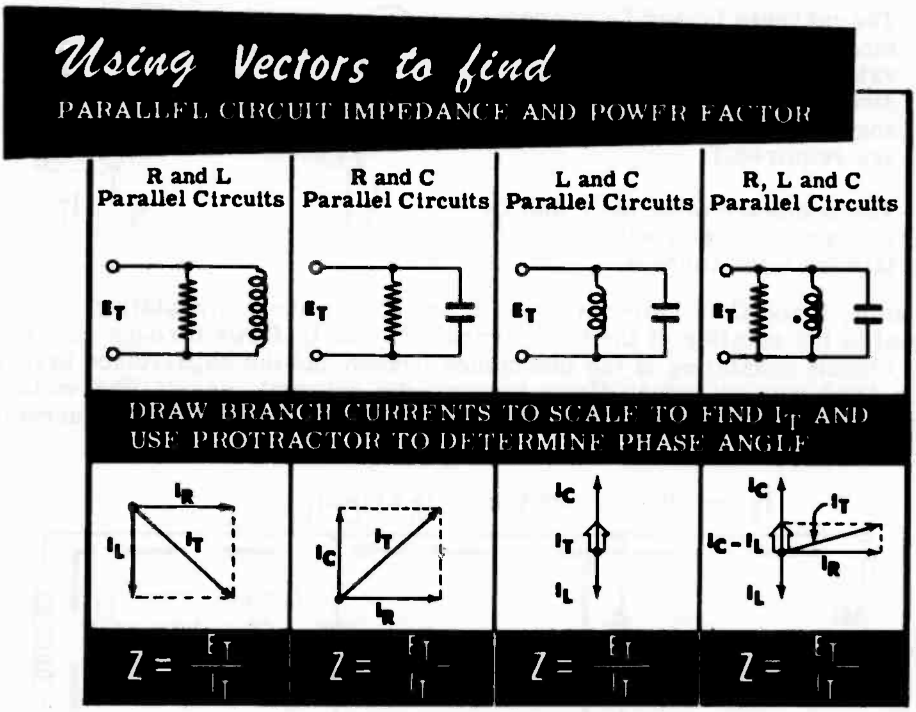
The impedance of a parallel circuit can be found using complicated vector or mathematical solutions, but the most practical method is to apply Ohm's law for AC to the total circuit. Using Ohm's law for AC, the impedance Z for all AC parallel circuits is found by dividing the circuit voltage by the total current $\left(Z = \frac{E_T}{I_T}\right)$.



OHM'S LAW FOR PARALLEL CIRCUIT IMPEDANCE . . . .

$$Z = \frac{E_T}{I_T}$$

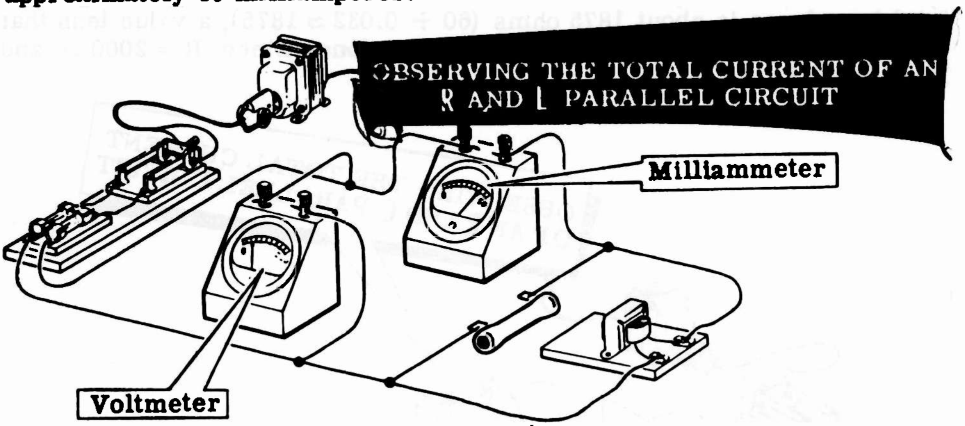
To find the impedance of a parallel circuit the total current is first found by using vectors; then Ohm's law for AC is applied to find Z. The steps used to find Z for the various types of AC parallel circuits are outlined below.



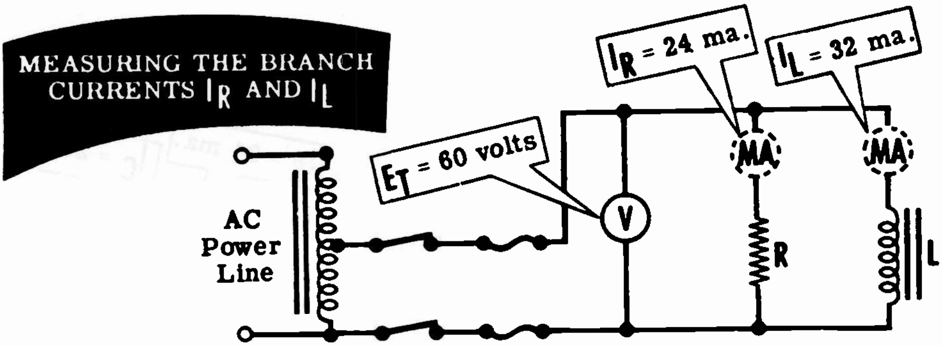
$$\text{POWER FACTOR} = \frac{I_R}{I_T}$$

Demonstration—R and L Parallel Circuit Current and Impedance

The current flow and the practical method of obtaining the impedance of an R and L parallel circuit is demonstrated first. The instructor connects a 2500-ohm, 20-watt resistor and a 5-henry filter choke in parallel across the AC power line through a step-down autotransformer, to form an AC parallel circuit of R and L. A 0-50 ma. AC milliammeter is connected to measure the total circuit current and a 0-250 volt range AC voltmeter is used to measure circuit voltage. With the power applied to the circuit, you see that the circuit voltage is about 60 volts and the total circuit current is approximately 40 milliamperes.



To measure the individual currents I_R and I_L through the resistor and the filter choke, the instructor first connects the milliammeter to measure only the resistor current, then to measure only the filter choke current. You see that the milliammeter reading for I_R is about 24 ma., and the current indicated for I_L is approximately 32 ma. The sum of these two branch currents I_R and I_L then is 56 ma. while the actual measured total circuit current is about 40 ma., showing that the branch currents must be added by means of vectors.

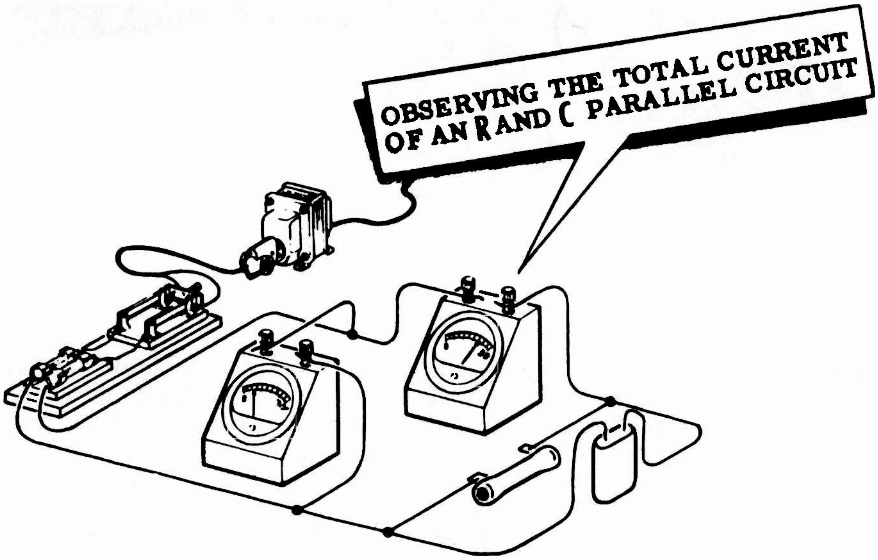


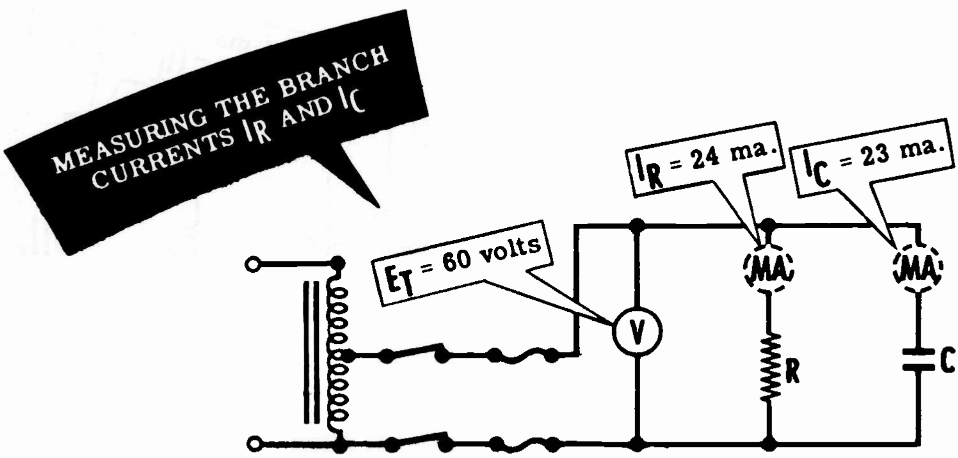
The calculated value of the impedance for this R and L circuit is 1500 ohms ($60 \div 0.040 = 1500$), indicating that the parallel connection of R and L reduces circuit impedance. The total circuit impedance is less than that of either branch of the circuit, since $R = 2500\Omega$ and $X_L = 1884\Omega$.

Demonstration—R and C Parallel Circuit Current and Impedance

Next the instructor replaces the 5-henry filter choke with a 1-mfd capacitor and repeats the previous demonstration. The total circuit voltage and current (E_T and I_T) is measured, and then the branch currents I_R and I_C are measured through the resistor and capacitor.

You see that the total circuit current I_T is approximately 32 ma., while the measured branch currents I_R and I_C are about 24 ma. and 23 ma. respectively. Again you see that the total current is less than the sum of the branch currents, due to the phase difference between I_R and I_C. The total impedance is about 1875 ohms ($60 \div 0.032 \approx 1875$), a value less than the opposition offered by either branch alone, since $R = 2000\,\Omega$ and $X_C = 2650\,\Omega$.

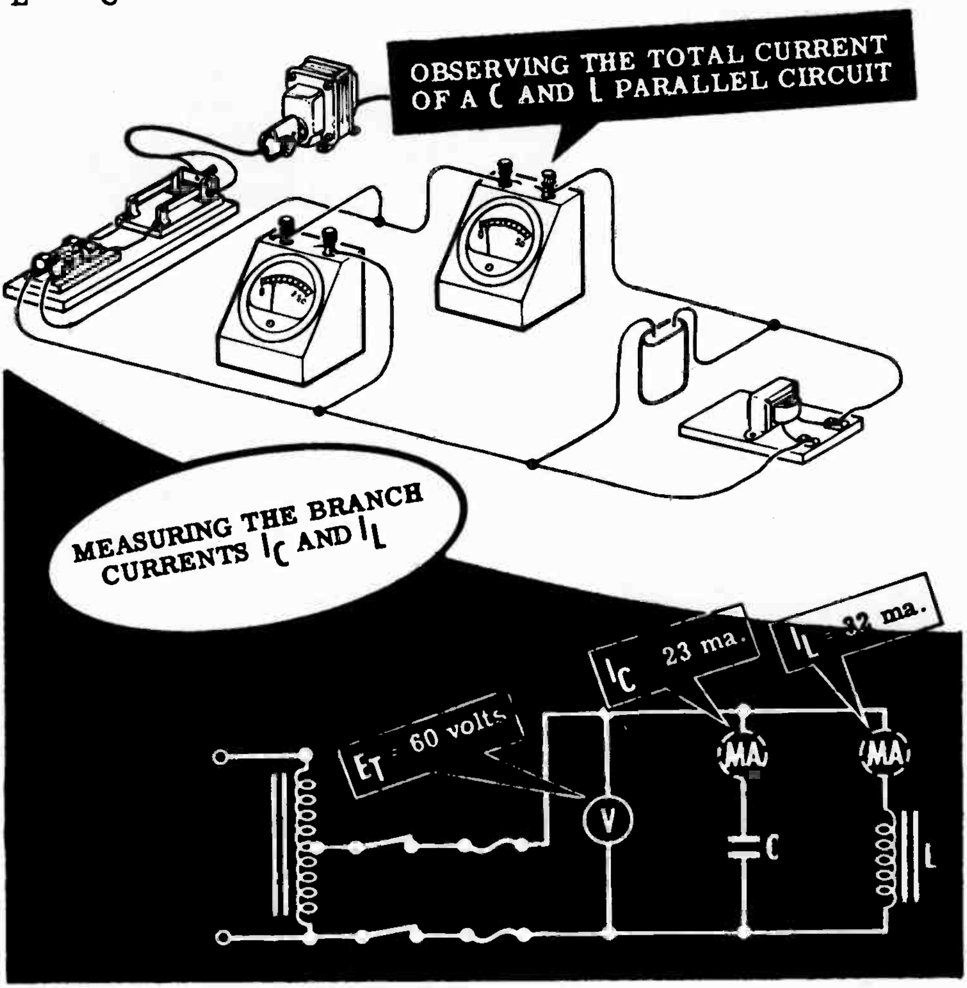




Demonstration—L and C Parallel Circuit Current and Impedance

To demonstrate the opposite effects of L and C in a parallel circuit, the 2500-ohm resistor is replaced by the 5-henry filter choke forming an L and C parallel circuit. Again the instructor repeats each step of the demonstration, first measuring the total circuit current, then that of each branch.

You see that the total circuit current is about 9 ma., while I_L is about 32 ma. and I_C is about 23 ma. Thus, the total current is not only less than that of either branch but is actually the difference between the currents I_L and I_C.

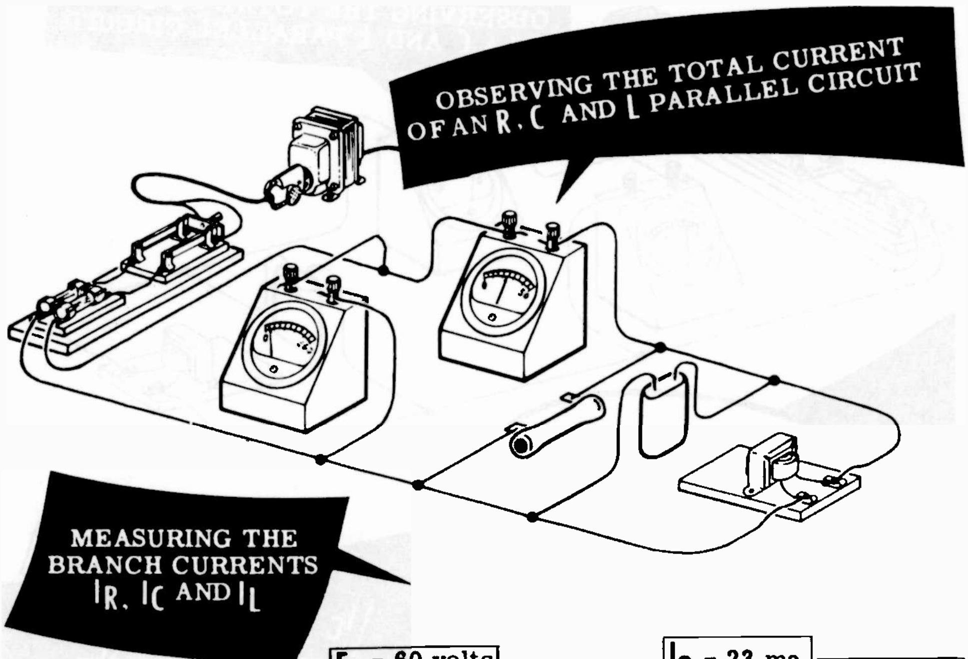


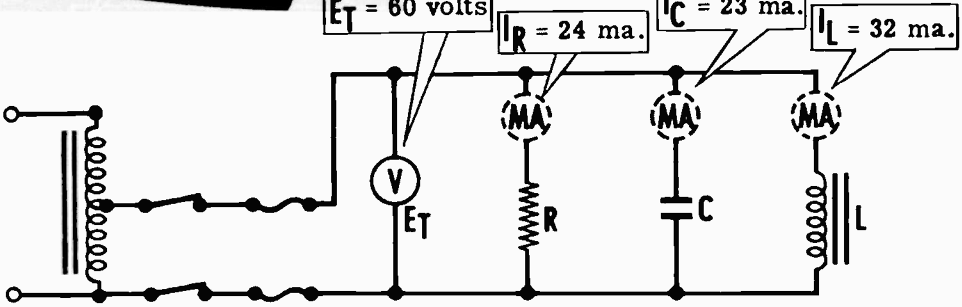
The total circuit impedance of the L and C circuit is 6700 ohms ($60 \div 0.009 \approx 6700$), a value greater than the opposition of either the L or C branch of the circuit. Notice that when L and C are both present in a parallel circuit the impedance increases, which is opposite in effect to that of a series circuit where combining L and C results in a lower impedance.

Demonstration—R, L and C Parallel Circuit Current and Impedance

By connecting a 2500-ohm, 20-watt resistor in parallel with the 5-henry filter choke and the 1-mfd capacitor, the instructor forms an R, L and C parallel circuit. To check the various currents and find the total circuit impedance he measures the total circuit current, then the individual currents through the resistor, filter choke and capacitor in turn.

Observe that the total circuit current increases and that the individual currents are the same as those previously measured in each branch. You see that I_R is 24 ma., I_L is 32 ma. and I_C is 23 ma. Again you see that the sum of the individual currents is much greater than the actual measured total current of 29 ma.

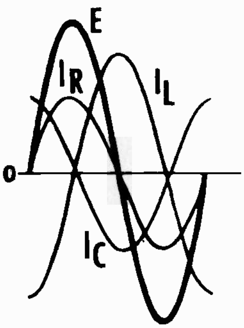


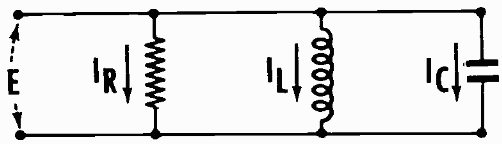


The total circuit impedance is about 2070 ohms ($60 \div 0.029 = 2070$). The total circuit current is the sum of the resistor current I_R and the combined inductance and capacitance currents I_L and I_C, added by means of vectors.

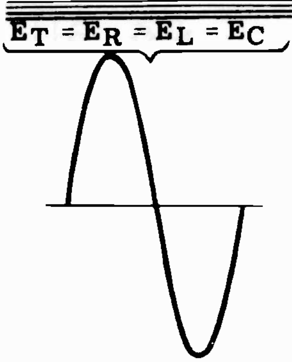
Review of AC Parallel Circuit Current and Impedance

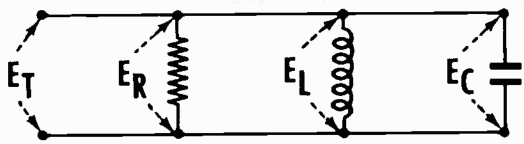
Consider what you have found out so far about AC parallel circuits. While reviewing parallel circuit current and impedance, compare the effects of series and parallel connections of R, L and C in AC circuits.



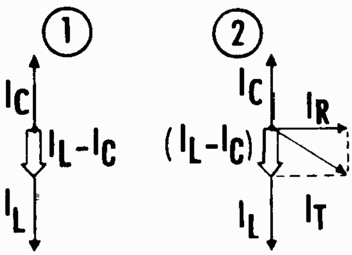


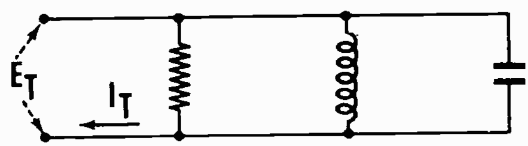
AC PARALLEL CIRCUIT CURRENT — The current divides to flow through the parallel branches. I_R is in phase with the circuit voltage, I_L lags the voltage by 90 degrees and I_C leads the voltage by 90 degrees.





AC PARALLEL CIRCUIT VOLTAGE — The voltage across each branch of a parallel circuit is equal to, and in phase with, that of each branch and that of the total circuit.





AC PARALLEL CIRCUIT IMPEDANCE AND POWER FACTOR — The impedance of an AC parallel circuit is equal to the circuit voltage divided by the total circuit current. The power factor equals the resistive current divided by the total circuit current.

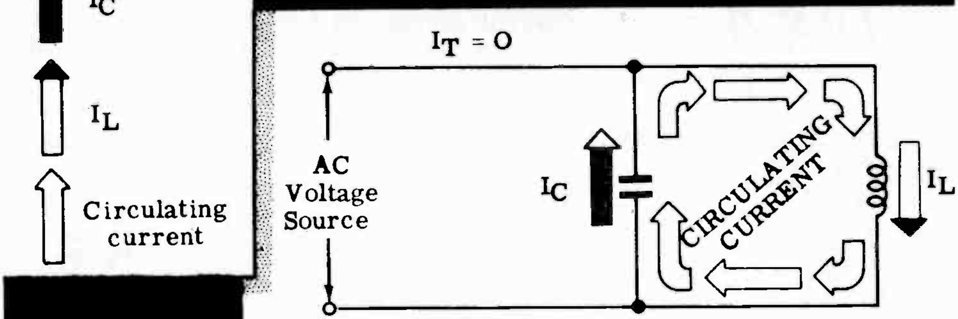
$$Z = \frac{E_T}{I_T}$$

$$P.F. = \frac{I_R}{I_T}$$

Parallel Circuit Resonance

In a parallel circuit containing equal X_L and X_C, the external circuit current is equal to that flowing through the parallel resistance. If the circuit contains no parallel resistance, the external current is zero. However, within a theoretical circuit consisting only of L and C and $X_L = X_C$, a large current called the "circulating current" flows, using no current from the power line. This occurs because the corresponding instantaneous values of the currents I_L and I_C always flow in opposite directions and, if these values are equal, no external circuit current will flow. This is called a "parallel resonant" circuit.

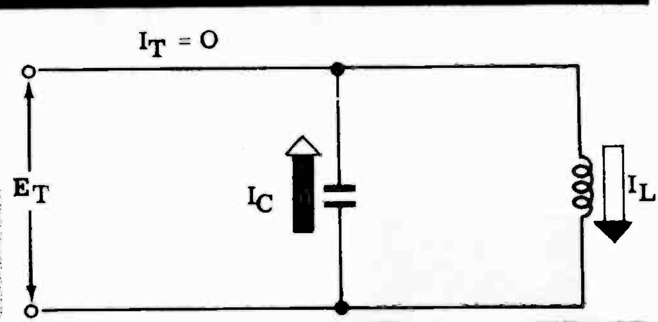
CURRENT FLOW IN A PARALLEL RESONANT CIRCUIT



Since $I_C = I_L$, the line current is zero and the circulating current is maximum.

Because no external current flows in a resonant parallel circuit consisting only of L and C, the impedance at resonance is infinite, I_L equals I_C, and the total circuit current I_T is zero. Since these effects are exactly opposite those of series resonance, parallel resonance is sometimes called "anti-resonance." Ohm's law for AC when applied to a parallel resonant circuit can be used to determine the value of the internal circulating current.

COMPUTING THE CIRCULATING CURRENT OF A PARALLEL RESONANT CIRCUIT

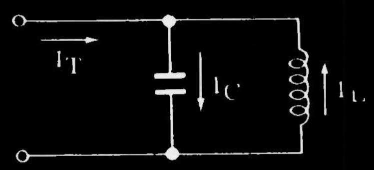


At resonance, $I_C = I_L$ and the circulating current equals either

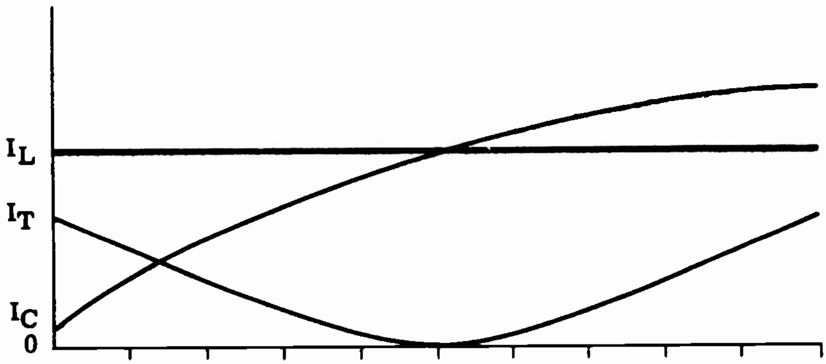
$$I_C = \frac{E_T}{X_C} \qquad I_L = \frac{E_T}{X_L}$$

Parallel Circuit Resonance (continued)

As in the case of a series resonant circuit, if either the frequency, inductive reactance or capacitive reactance of a circuit is varied and the two other values kept constant, the circuit current variation forms a resonance curve. However, the parallel resonance curve is the opposite of a series resonance curve. The series resonance current curve increases to a maximum at resonance then decreases as resonance is passed, while the parallel resonance current curve decreases to a minimum at resonance then increases as resonance is passed.



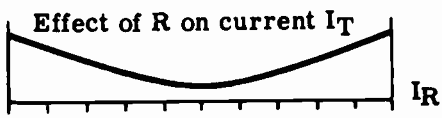
VARYING THE CAPACITANCE OF A PARALLEL CIRCUIT THROUGH RESONANCE VARIES THE CURRENTS I_C AND I_L



Varying values of capacitance

I_T is the difference between I_L and I_C

For a circuit of pure L and C the curve would be as shown above. However, all actual capacitors and inductors have some resistance which prevents the current from becoming zero.

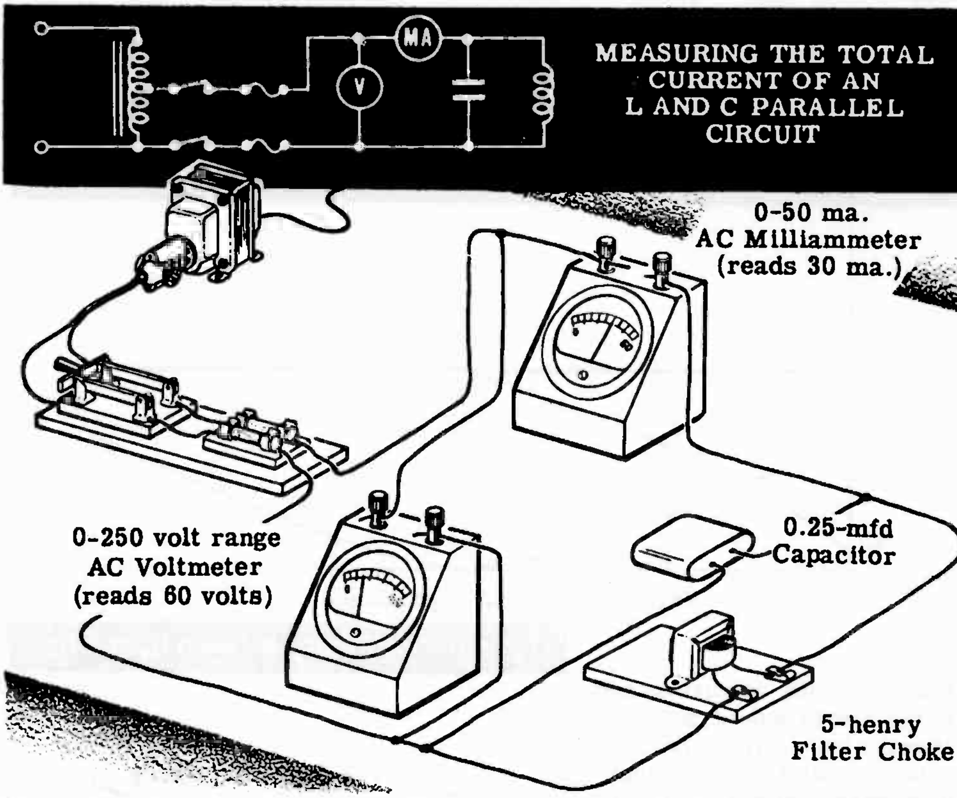


A comparison of circuit factors at resonance for series and parallel circuits, made in chart form, is shown below.

Series Resonance		Parallel Resonance
Equal across X_L and X_C	VOLTAGE	Equal across each circuit branch
Maximum	CURRENT	Minimum
Minimum	IMPEDANCE	Maximum

Demonstration—Parallel Circuit Resonance

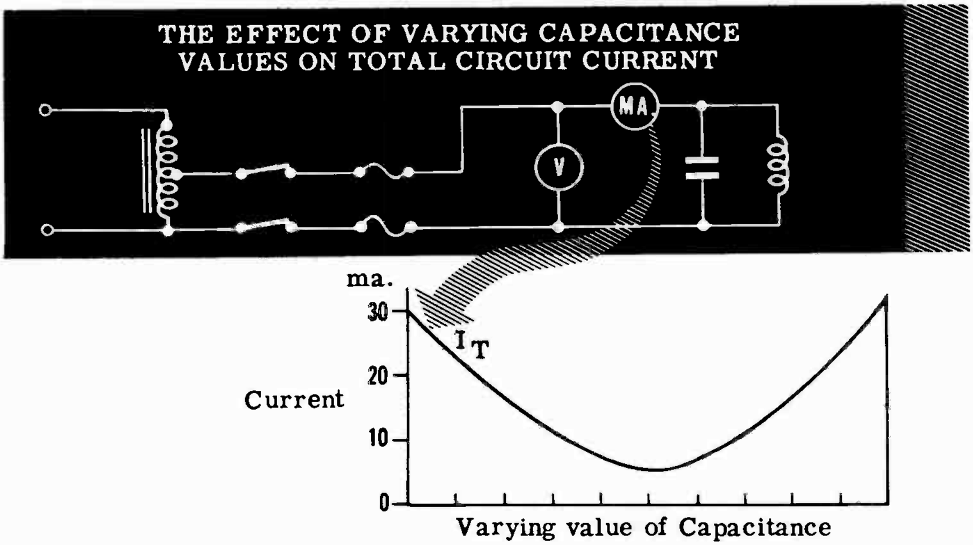
To show how parallel resonance affects parallel circuit current, the instructor connects a 0.25-mfd capacitor and a 5-henry filter choke in parallel to form an L and C parallel circuit. A 0-50 ma. AC milliammeter and a 0-250 volt range AC voltmeter are connected to measure circuit current and voltage. This circuit is connected to the AC power line through a switch, fuses and step-down autotransformer. When the switch is closed, you observe that the circuit current is about 30 ma. and the voltage is approximately 60 volts.



The total current indicated by the meter reading is actually the difference between the currents I_L and I_C through the inductive and capacitive branches of the parallel circuit. Because a meter connected in series with either of the branches would add resistance to that branch, causing inaccurate readings, the branch currents are not read. The circuit voltage remains constant in parallel circuits so that, if a fixed value of inductance is used as one branch of the circuit, the current in that branch remains constant. If the capacitance of the other branch is varied, its current varies as the capacity varies, being low for small capacitance values and high for large capacitance values. The total circuit current is the difference between the two branch currents and is zero when the two branch currents become equal. As the instructor increases the circuit capacitance, the total current will drop as the current I_C increases toward the constant value of I_L, will be zero when I_C equals I_L and then will rise as I_C becomes greater than I_L.

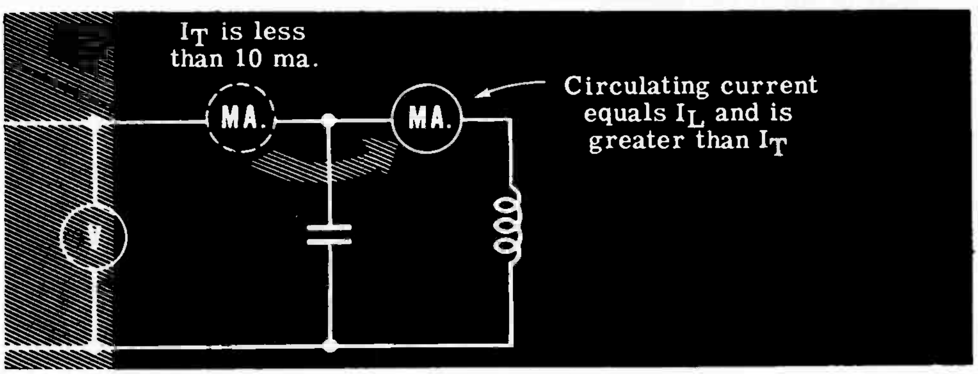
Demonstration—Parallel Circuit Resonance (continued)

The instructor varies the circuit capacitance in steps of 0.25 mfd from 0.25 mfd through 2.5 mfd. Observe that the current decreases from approximately 30 ma. to a minimum value less than 10 ma., then rises to a value beyond the range of the milliammeter. The current at resonance does not reach zero because the circuit branches are not purely capacitive and inductive and cannot be so in a practical parallel circuit. You also observe that the voltage does not change across either the branches or the total parallel circuit as the capacitance value is changed.



After the value of capacitance has been varied through the complete range of values, the value which indicates resonance—minimum current flow—is used to show that the circulating current exceeds the line current at resonance. The instructor again measures the line current of the parallel resonant circuit, then connects the milliammeter to measure only the current in the inductive branch. You see that the total current is less than 10 ma., yet the circulating current is approximately 30 ma.

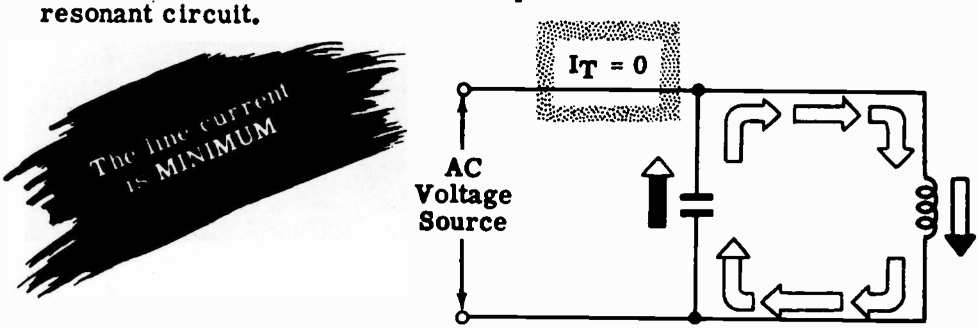
CHECKING THE VALUE OF CIRCULATING CURRENT
IN A PARALLEL RESONANT CIRCUIT



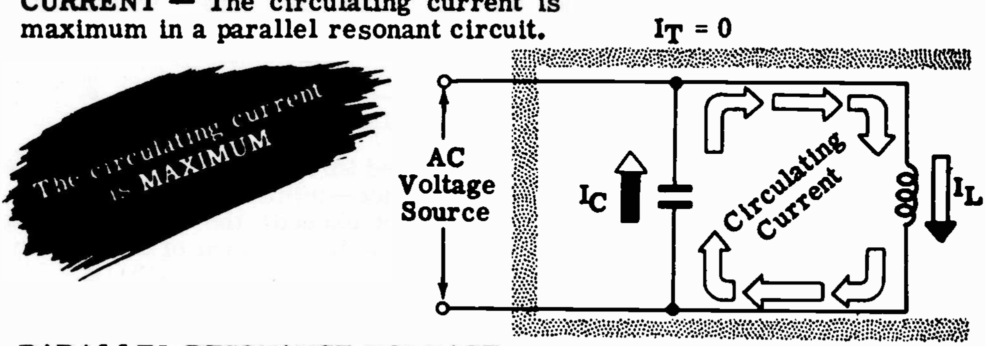
Review of Parallel Circuit Resonance

You have found that the effect of parallel circuit resonance on circuit current is exactly opposite to that of series resonance. Also, you have seen parallel resonance demonstrated, showing how it affects both line current and circulating current. Before performing the experiment on parallel resonance, suppose you review its effects on current and voltage.

PARALLEL RESONANCE LINE CURRENT — The line current is minimum in a parallel resonant circuit.

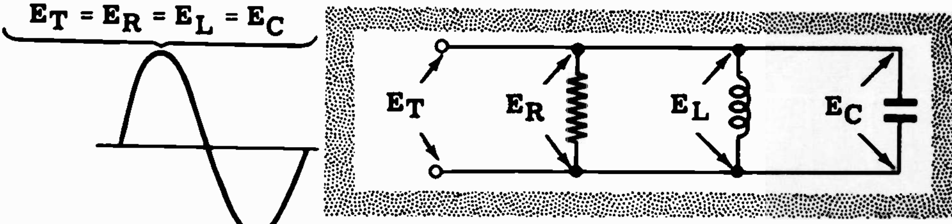


PARALLEL RESONANCE CIRCULATING CURRENT — The circulating current is maximum in a parallel resonant circuit.



PARALLEL RESONANCE VOLTAGE — The voltage of parallel circuit branches at resonance is the same as the voltage when the circuit is not at resonance.

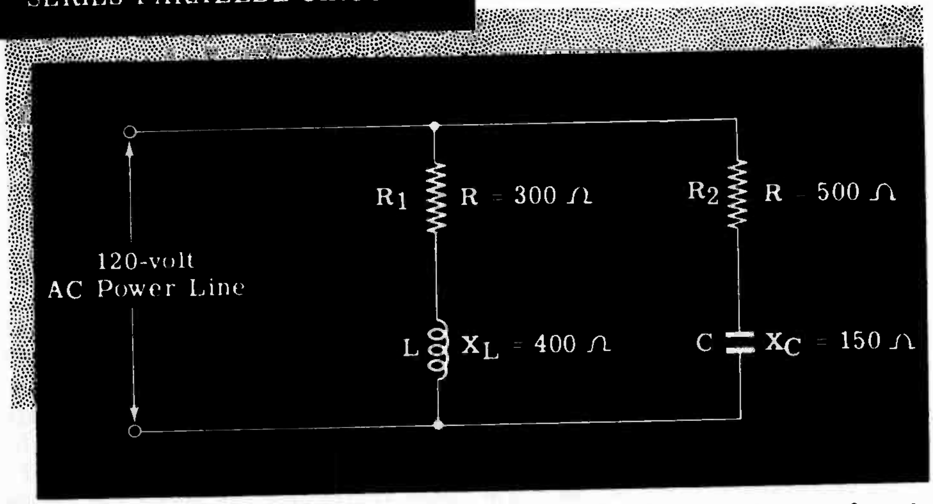
$$\underbrace{E_T = E_R = E_L = E_C}$$



Complex AC Circuits

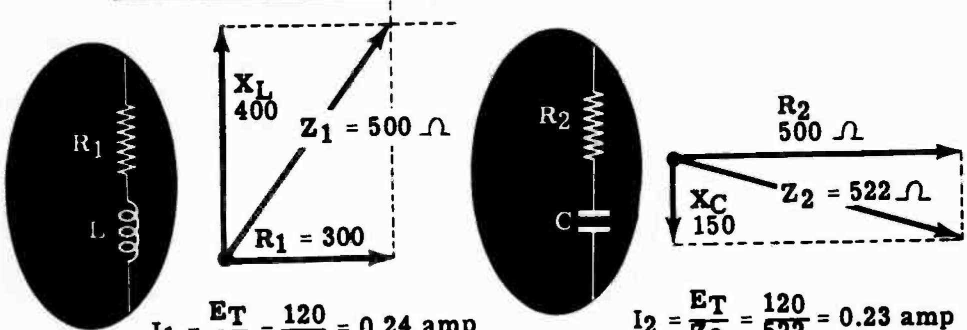
Many AC circuits are neither series nor parallel circuits but are a combination of these two basic circuits. Such circuits are called "series-parallel" or "complex" circuits and, as in DC circuits, they contain both parallel parts and series parts. The values and phase relationships of the voltages and currents for each particular part of a complex circuit depend on whether the part is series or parallel. Any number of series-parallel combinations form complex circuits and, regardless of the circuit variations, the step-by-step vector solution is similar to the solution of DC complex circuits. The parts of the circuit are first considered separately, then the results are combined. For example, suppose your circuit consists of the series-parallel combination shown below, with two separate series circuits connected in parallel across a 120-volt AC power line. The vector solution used to find the total circuit current, total impedance and the circuit phase angle is outlined below:

SERIES-PARALLEL CIRCUIT



To find the values of the branch currents I_1 and I_2, the impedance of each branch is found separately by using vectors. The current values are then determined by applying Ohm's law to the branches separately.

FINDING THE IMPEDANCES OF EACH BRANCH



$I_1 = \frac{E_T}{Z_1} = \frac{120}{500} = 0.24$ amp

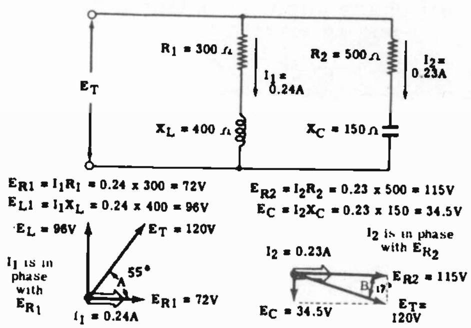
$I_2 = \frac{E_T}{Z_2} = \frac{120}{522} = 0.23$ amp

Complex AC Circuits (continued)

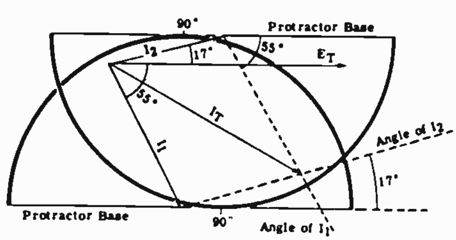
Although you know the branch currents I_1 and I_2, the total current I_T cannot be found by adding I_1 and I_2 directly. Since they are out of phase, the instantaneous values for each branch current are not equal.

To find the phase relationship between I_1 and I_2 so that they may be added by using vectors, the voltage and current vectors for each series branch must first be drawn separately. (Since the values of I_1 and I_2 are known, the voltages across the various parts of each series branch can be found by applying Ohm's law.)

VOLTAGE AND CURRENT VECTORS FOR EACH BRANCH

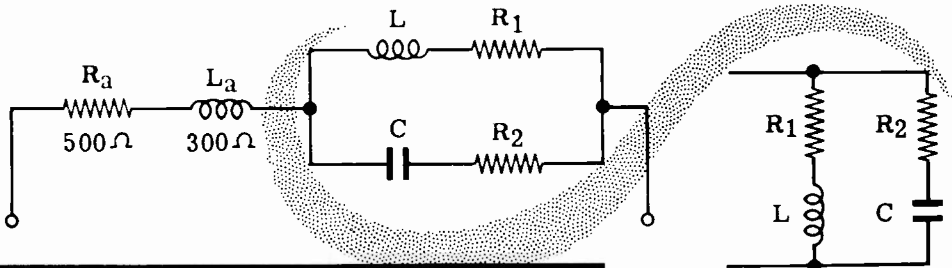


The vector solutions for each separate branch, when drawn to scale, show both the values and the phase relationships between the branch currents and the total circuit voltage, E_T. To show the phase relation between I_1 and I_2, they are redrawn with respect to E_T which is drawn horizontally as the reference vector. Draw I_1 down in relation to E_T at the angle found vectorally. I_1 lags the voltage as the branch has the inductor in it. Draw I_2 up in relation to E_T,at the angle found vectorally. I_2 leads the voltage as the branch has the capacitor in it. Lay the protractor at the end of I_1 with the vertical line up and the base horizontal to the reference line E_T. Mark off an angle equal to the angle of the I_2 vector. Next lay the protractor at the end of I_2 with the vertical line down and the base horizontal to the reference line E_T. Mark off an angle equal to the angle of the I_1 vector. Complete the parallelogram by drawing a dotted line from the end of each vector to the point marked off from your protractor. From the reference point draw a line to where the two dotted lines cross. This vector represents the total current of the circuit. Measure with the protractor the angle between I_T and E_T and this will be the phase angle of the circuit.



Complex AC Circuits (continued)

Series-parallel circuits may be even more complex than the one just illustrated. For example, suppose that the series-parallel circuit is connected in series with an inductance and a resistance as shown below.

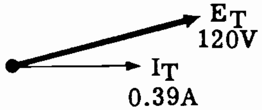


A COMPLEX CIRCUIT CONTAINING A SERIES-PARALLEL CIRCUIT

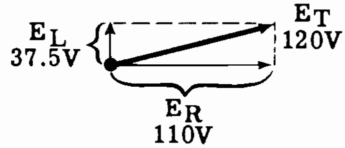
To find the total circuit current and impedance, the vectors I_T and E_T are redrawn with I_T as the horizontal reference vector. The phase angle between these two vectors is positive, indicating that inductance more than cancels capacitance in the parallel part of the circuit. Therefore, this part of the circuit can be replaced by an R and L series circuit since the value of E_T in the parallel circuit is the result of adding the vector voltages, E_R and E_L. By completing the parallelogram, the voltages E_L and E_R across this series circuit can be determined. The resistance and inductive reactance (X_{L_e} and R_e) of this equivalent series circuit can be found by using the vector voltages and the total current, then applying Ohm's law. (Although the voltage across the parallel part of the complex circuit may not be 120 volts, the computed values of R and X_C for the equivalent circuit are the same regardless of the voltage, actual or assumed, across this part of the circuit.)

FINDING THE EQUIVALENT SERIES CIRCUIT OF THE SERIES-PARALLEL CIRCUIT

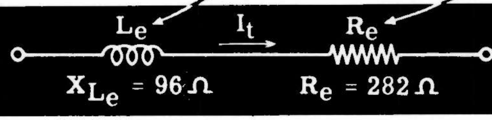
1. Draw E_T in relation to I_T



2. Find individual voltages which combine to form E_T



3. Since I_t flows through L_e and R_e ⟶ $X_{L_e} = \frac{37.5}{0.39} = 96\Omega$ $R_e = \frac{110}{0.39} = 282\Omega$

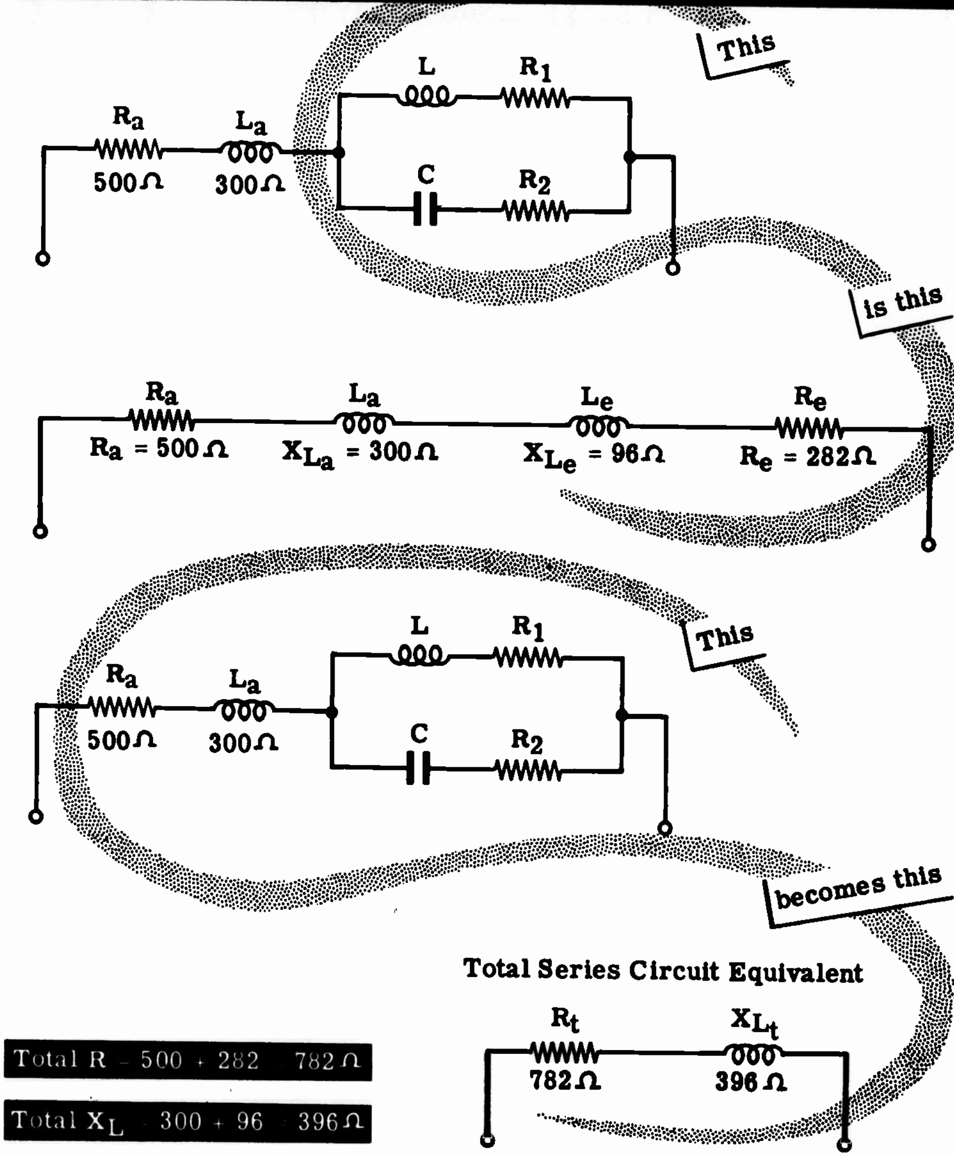


Equivalent Series Circuit

Complex AC Circuits (continued)

By replacing the parallel part of the complex circuit with the equivalent R_e and X_{L_e} values, the circuit becomes a series circuit. Combining the two values of R and the two values of X_L results in a simple R and L series circuit, which would have the same effect on total circuit current and voltage as the entire complex circuit. To find the value of total circuit impedance and current flow, the simple series circuit is then solved by using vectors.

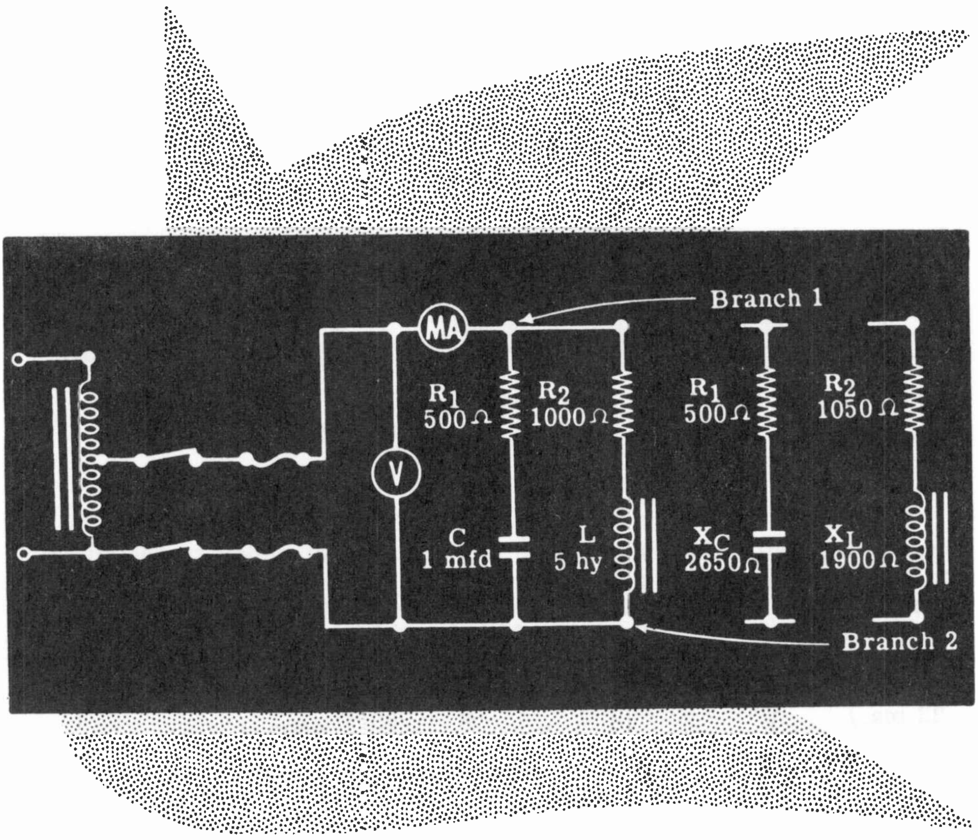
Substituting the EQUIVALENT SERIES CIRCUIT for the SERIES-PARALLEL CIRCUIT



Demonstration of Complex Circuits

For demonstration purposes, a series-parallel circuit containing resistance, inductance and capacitance is used. The instructor will demonstrate the method of solving such circuits to find the total circuit current, the branch currents, the impedance and the equivalent series circuit. The calculated results will be checked with actual voltage and current measurements, and you will see how the values compare. Because pure inductances and pure capacitances are only theoretical, there will be a noticeable difference between the actual and calculated results. However, the measured results will show that the calculations are accurate enough for practical use in electrical circuits.

The instructor connects a 500-ohm resistor, a 1000-ohm resistor, a 1-mfd capacitor and a 5-henry filter choke to form the complex circuit shown below. Because the filter choke has a DC resistance of approximately 50 ohms, the total resistance of the R and L branch of the circuit is 1050 ohms. R_2 is rated as a 1050-ohm resistor rather than a 1000-ohm resistor.

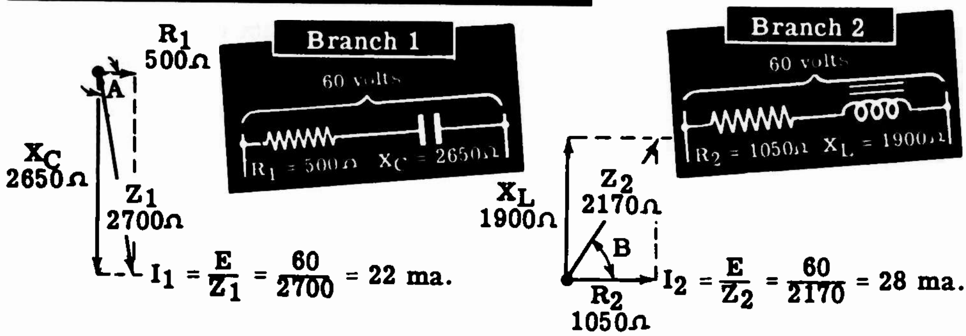


Demonstration—Vector Solution of Complex Circuits

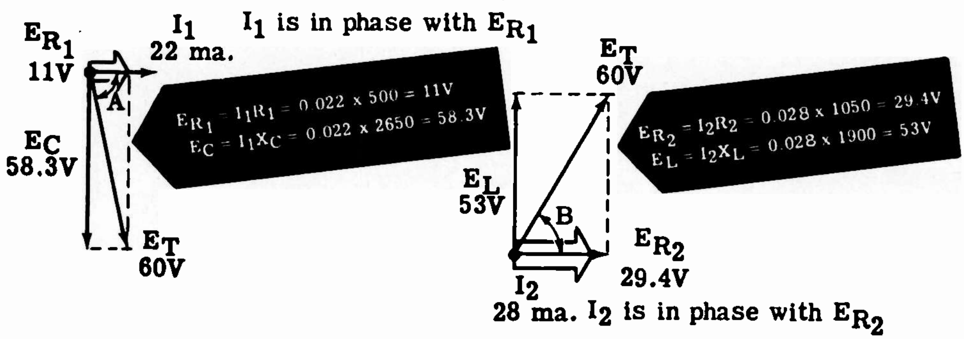
Before applying power to the circuit, the instructor demonstrates the vector solution to find the total current, branch currents and impedance. First the values of X_L and X_C are computed, using 60 cycles as the power line frequency. Rounded off to the nearest 50 ohms, these values are 1900 ohms for X_L and 2650 ohms for X_C.

Using the known values of R_1 and R_2 together with the computed values of X_L and X_C, the impedances of each series branch are found separately by using vectors. From these values of impedance and a source voltage of 60 volts, the values of the branch currents I_1 and I_2 are found.

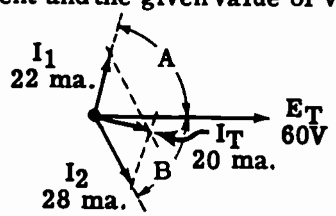
FIND THE BRANCH CURRENTS I_1 AND I_2



Next the individual voltages of each branch are drawn with respect to their corresponding branch current, to find the relationship between E_T and each of the branch currents individually.



These individual relationships are drawn with reference to the common total voltage vector, E_T, and the two branch current vectors are combined to find the total circuit current. From the computed value of the total current and the given value of voltage, 60 volts, the total impedance is computed.

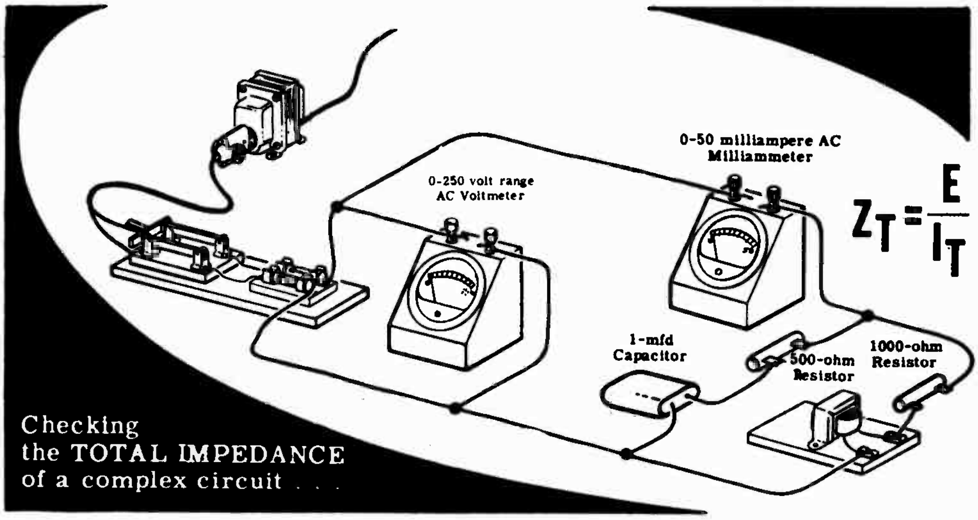


$$Z_T = \frac{E}{I_T} = \frac{60}{.020} = 3000\ \Omega$$

Z_T is approximately 3000 ohms

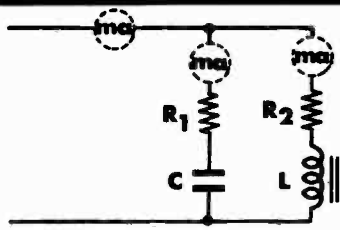
Demonstration—Complex Circuit Currents and Impedance

To check the computed values of the total current and circuit impedance, the instructor applies power to the circuit and measures the total circuit current and voltage. You see that the measured total current and voltage are approximately the same as the computed values. From these measured values the impedance Z_T is determined and compared to the value obtained by using vectors.



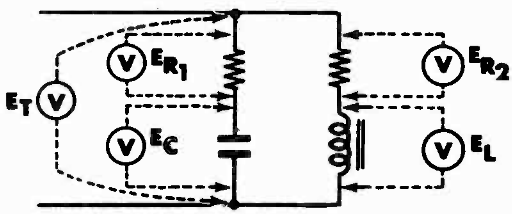
MEASURING THE BRANCH CURRENTS

Next the instructor connects the milliammeter to measure each branch current in turn. You see that the measured values are about the same as the computed values, and that the total circuit current is less than the sum of the two branch currents.



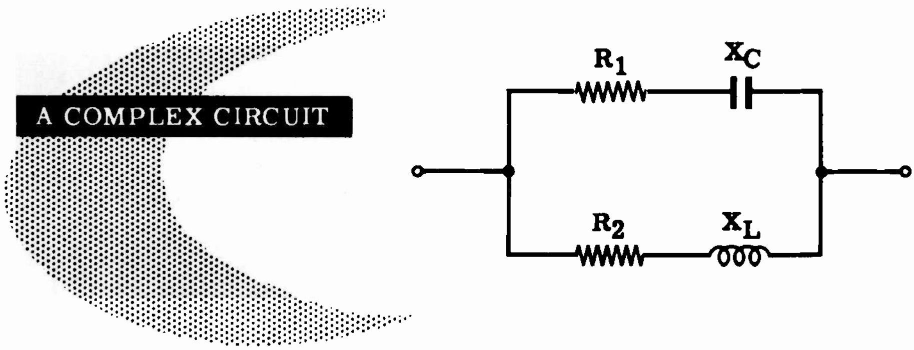
MEASURING THE CIRCUIT VOLTAGES

To check the computed values of the various voltages in the circuit, the instructor measures the voltage across each resistor, the capacitor and the inductance. You see that the sum of the voltages across each branch is greater than the total voltage and that the measured voltages are nearly equal to the computed values.



Review of AC Complex Circuits

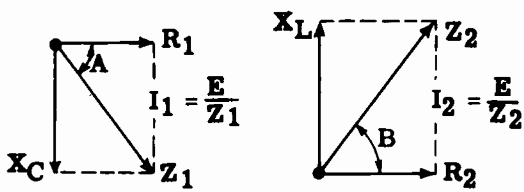
The solution of a complex AC circuit requires a step-by-step use of vectors and Ohm's law to find unknown quantities of voltage, current and impedances. Suppose you review the vector solution of a typical complex circuit:



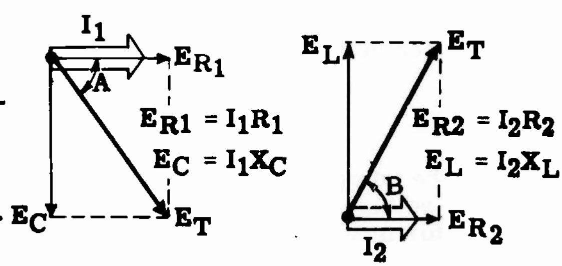
1. Calculate the reactance values of circuit capacitances and/or inductances.

$$X_C = \frac{1}{2\pi fC} \qquad X_L = 2\pi fL$$

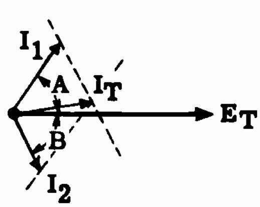
2. Using vectors, find the impedance of each series branch separately, and compute the Ohm's law values of the branch currents.



3. Compute the individual voltages of each branch and draw them with respect to their respective branch current. Complete the voltage parallelograms to find the phase relationship between each branch current and the total circuit voltage.



4. Draw the branch current vectors with respect to a common total circuit voltage vector, then combine the currents to find the total circuit current. Calculate the total impedance of the circuit.



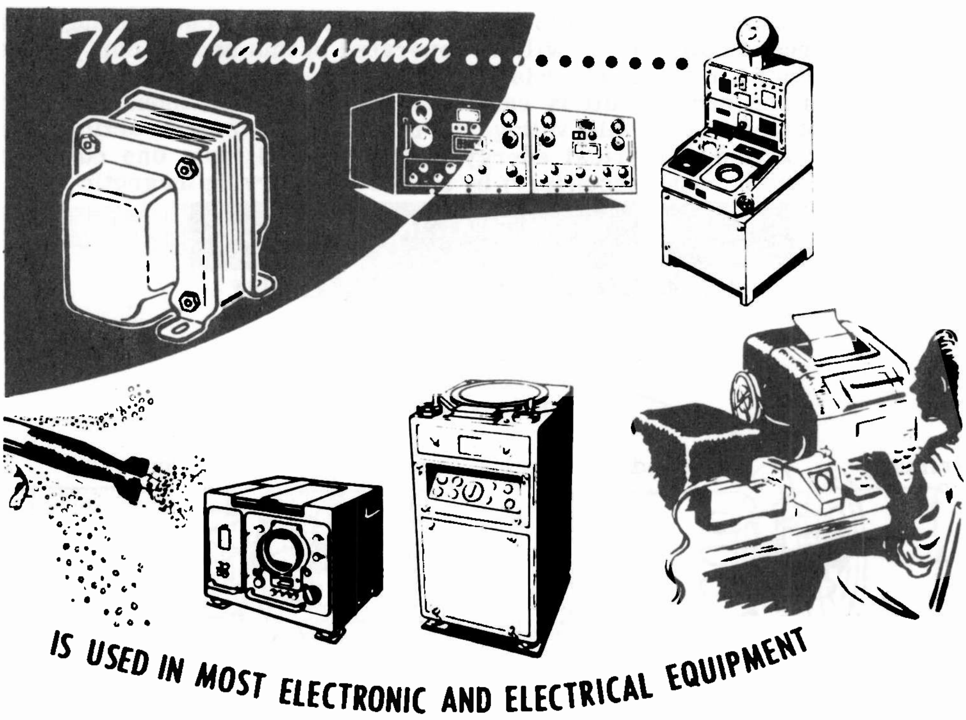
$$Z_T = \frac{E}{I_T}$$

The Importance Of Transformers

When you studied AC circuits, you learned that alternating current as a source of power has certain advantage over direct current. The most important advantage of AC is that the voltage level can be raised or lowered by means of a transformer. You remember it is better to transmit power over long distances at a high voltage and low current level, since the IR drop due to the resistance of the transmission lines is greatly reduced.

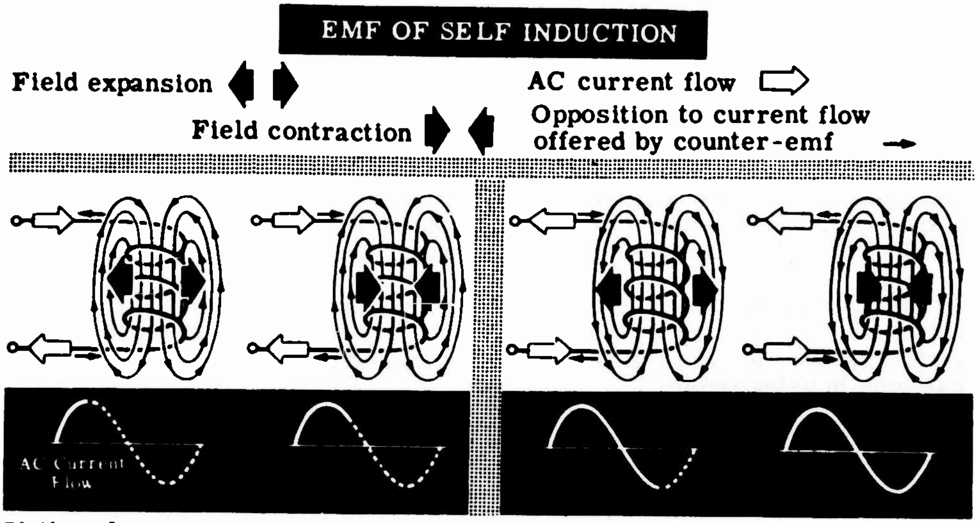
To transmit AC power at a high voltage low current level, the generated voltage is fed into a transformer. The transformer raises the voltage, and since power depends on both voltage and current, a higher voltage means the same amount of power will require a lower current. At the load end of the transmission line, another transformer reduces the voltage to the level necessary to operate the load equipment. For example, at Niagara Falls AC is generated at 6000 volts, stepped up by transformers to 120,000 volts and distributed over long transmission lines, stepped down at different points to 6000 volts for local distribution, and finally stepped down to 220 and 110 volts AC for lighting and local power use.

Transformers are used in all types of electronic equipment, to raise and lower AC voltages. It is important for you to become familiar with transformers, how they work, how they are connected into circuits, and precautions in using them.

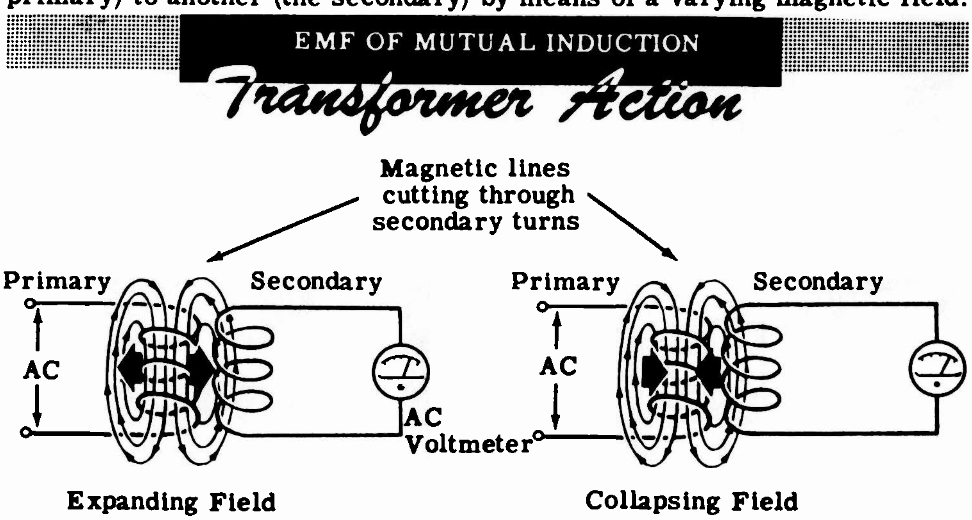


How a Transformer Works

When AC flows through a coil, an alternating magnetic field is generated around the coil. This alternating magnetic field expands outward from the center of the coil and collapses into the coil as the AC through the coil varies from zero to a maximum and back to zero again. Since the alternating magnetic field must cut through the turns of the coil an emf of self induction is induced in the coil which opposes the change in current flow



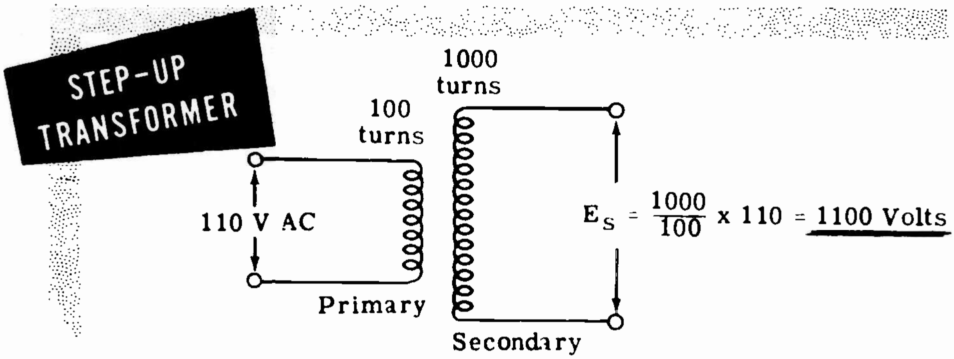
If the alternating magnetic field generated by one coil cuts through the turns of a second coil, an emf will be generated in this second coil just as an emf is induced in a coil which is cut by its own magnetic field. The emf generated in the second coil is called the "emf of mutual induction," and the action of generating this voltage is called "transformer action." In transformer action, electrical energy is transferred from one coil (the primary) to another (the secondary) by means of a varying magnetic field.

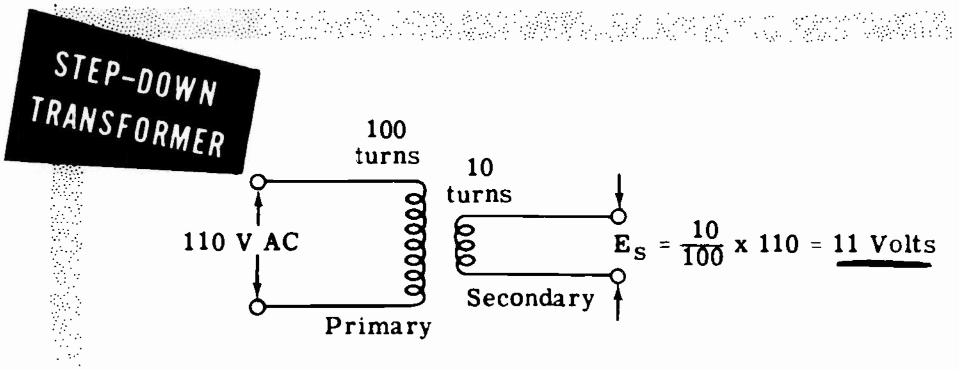


How a Transformer Works (continued)

A simple transformer consists of two coils very close together, electrically insulated from each other. The coil to which the AC is applied is called the "primary." It generates a magnetic field which cuts through the turns of the other coil, called the "secondary," and generates a voltage in it. The coils are not physically connected to each other. They are, however, magnetically coupled to each other. Thus, a transformer transfers electrical power from one coil to another by means of an alternating magnetic field.

Assuming that all the magnetic lines of force from the primary cut through all the turns of the secondary, the voltage induced in the secondary will depend on the ratio of the number of turns in the secondary to the number of turns in the primary. For example, if there are 1000 turns in the secondary and only 100 turns in the primary, the voltage induced in the secondary will be 10 times the voltage applied to the primary ($\frac{1000}{100} = 10$). Since there are more turns in the secondary than there are in the primary, the transformer is called a "step-up transformer." If, on the other hand, the secondary has 10 turns and the primary has 100 turns, the voltage induced in the secondary will be one-tenth of the voltage applied to the primary ($\frac{10}{100} = \frac{1}{10}$). Since there are less turns in the secondary than there are in the primary, the transformer is called a "step-down transformer." Transformers are rated in KVA because it is independent of power factor.



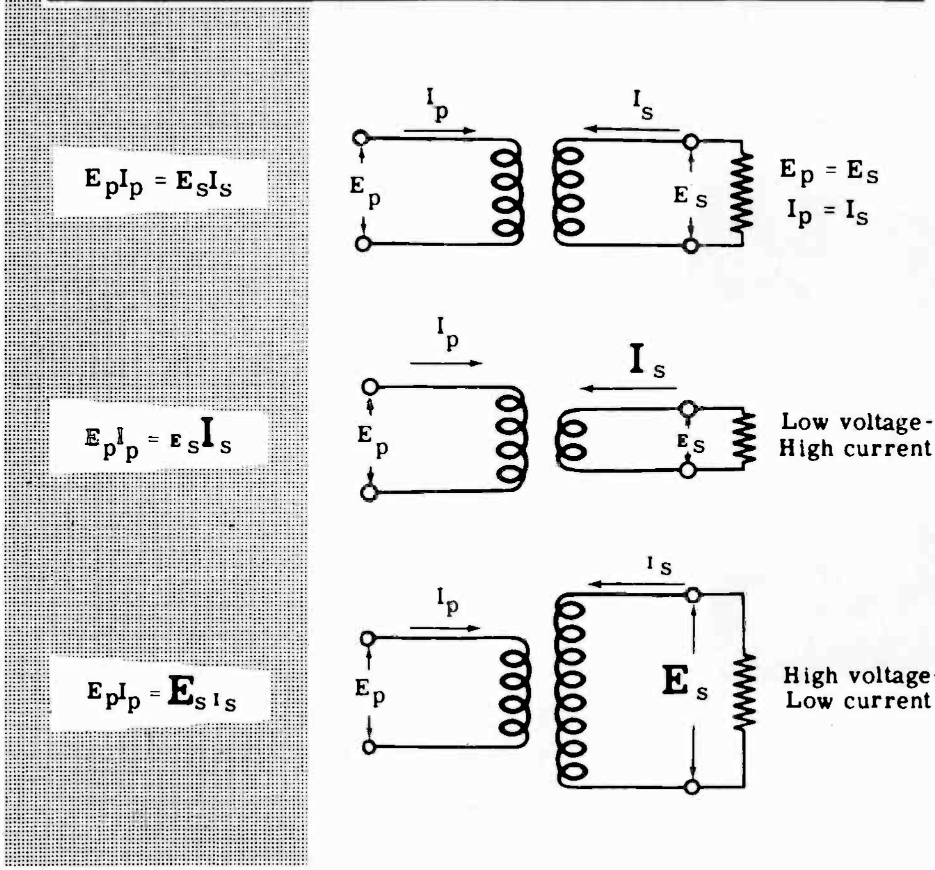


How a Transformer Works (continued)

A transformer does not generate electrical power. It simply transfers electric power from one coil to another by magnetic induction. Although transformers are not 100 percent efficient, they are very nearly so. For practical purposes, their efficiency is considered to be 100 percent. Therefore, a transformer can be defined as a device that transfers power from its primary circuit to the secondary circuit without any loss (assuming 100 percent efficiency).

Since power equals voltage times current, if E_pI_p represents the primary power and E_sI_s represents the secondary power, then $E_pI_p = E_sI_s$. If the primary and secondary voltages are equal, the primary and secondary currents must also be equal. Suppose E_p is twice as large as E_s. Then, in order for E_pI_p to equal E_sI_s, I_p must be one half of I_s. Thus a transformer which steps voltage down, steps current up. Similarly, if E_p is only half as large as E_s, I_p must be twice as large as I_s and a transformer which steps voltage up, steps current down. Transformers are classified as step-down or step-up only in relation to their effect on voltage.

PRIMARY POWER EQUALS SECONDARY POWER



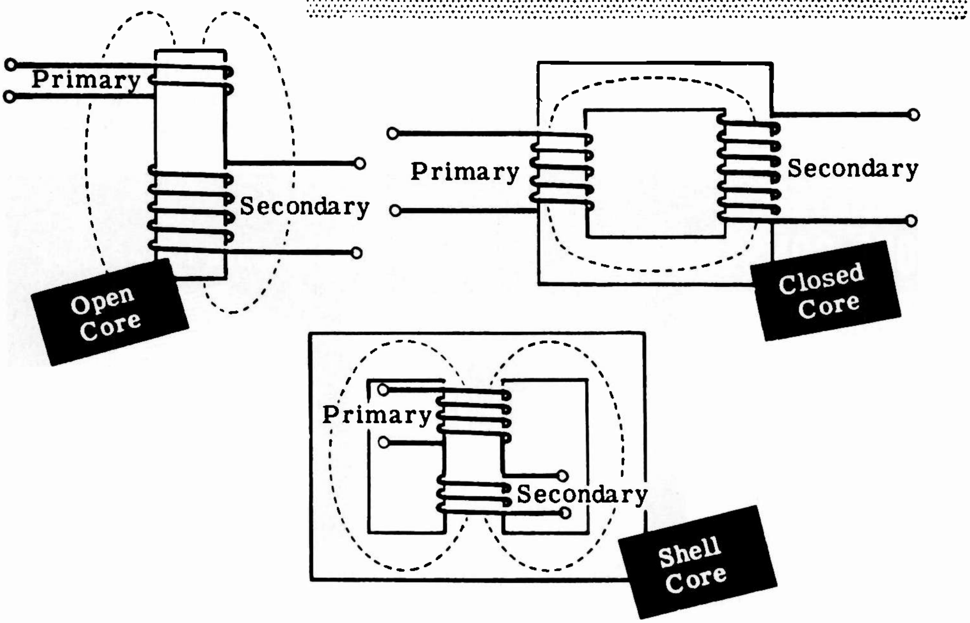
Transformer Construction

Transformers designed to operate on low frequencies have their coils, called "windings," wound on iron cores. Since iron offers little resistance to magnetic lines, nearly all the magnetic field of the primary flows through the iron core and cuts the secondary. The iron core increases the efficiency of the transformer to 98 or 99 percent, which can practically be considered 100 percent, or "no loss."

Iron cores are constructed in three main types—the open core, the closed core and the shell type. The open core is the least expensive to build—the primary and the secondary are wound on one cylindrical core. The magnetic path is partly through the core, partly through the air. The air path opposes the magnetic field, so that the magnetic interaction or "linkage" is weakened. The open core transformer is inefficient and never used for power transfer.

The closed core improves the transformer efficiency by offering more iron paths and less air path for the magnetic field, thus increasing the magnetic "linkage" or "coupling." The shell type core further increases the magnetic coupling and therefore the transformer efficiency, because it provides two parallel magnetic paths for the magnetic field. Thus maximum coupling is attained between the primary and secondary.

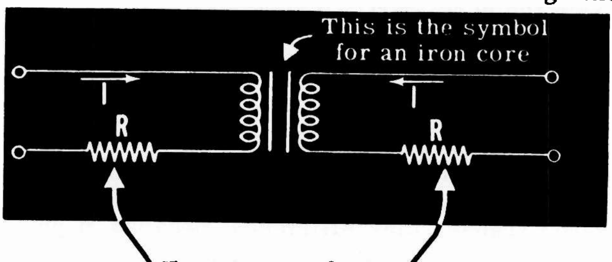
TRANSFORMER CORE CONSTRUCTION. . . .



Transformer Losses

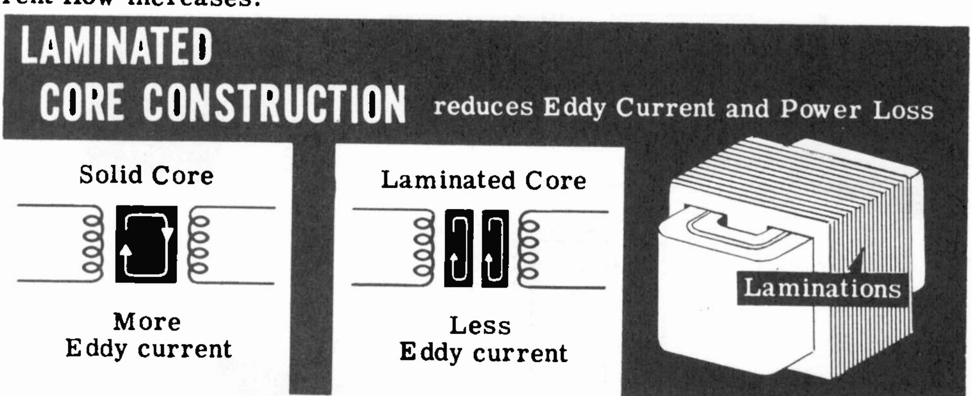
Not all of the electrical energy from the primary coil is transferred to the secondary coil. A transformer has some losses; and the actual efficiency, although usually greater than 90 percent, is less than 100 percent. Transformer losses are generally of two types—"copper losses" and "core losses."

Copper losses represent the power loss in resistance of the wire in the windings. These are called copper losses since copper wire usually is used for the windings. Although normally the resistance of a winding is not high, current flow through the wire causes it to heat, using power. This power can be computed from the formula I^2R, where R is the coil wire resistance and I is the current through the coil.



Resistance of wire results in **COPPER LOSSES** in a transformer

Core losses are due to eddy currents and hysteresis. The magnetic field which induces current in the secondary coil also cuts through the core material, causing a current, called "eddy current," to flow through the core. This eddy current heats the core material—an indication that power is being used. If the resistance of the eddy current path is increased less current will flow, reducing the power losses. By laminating the core material, that is by using thin sheets of metal insulated by varnish—the cross-section of each current path is diminished, and the resistance to eddy current flow increases.



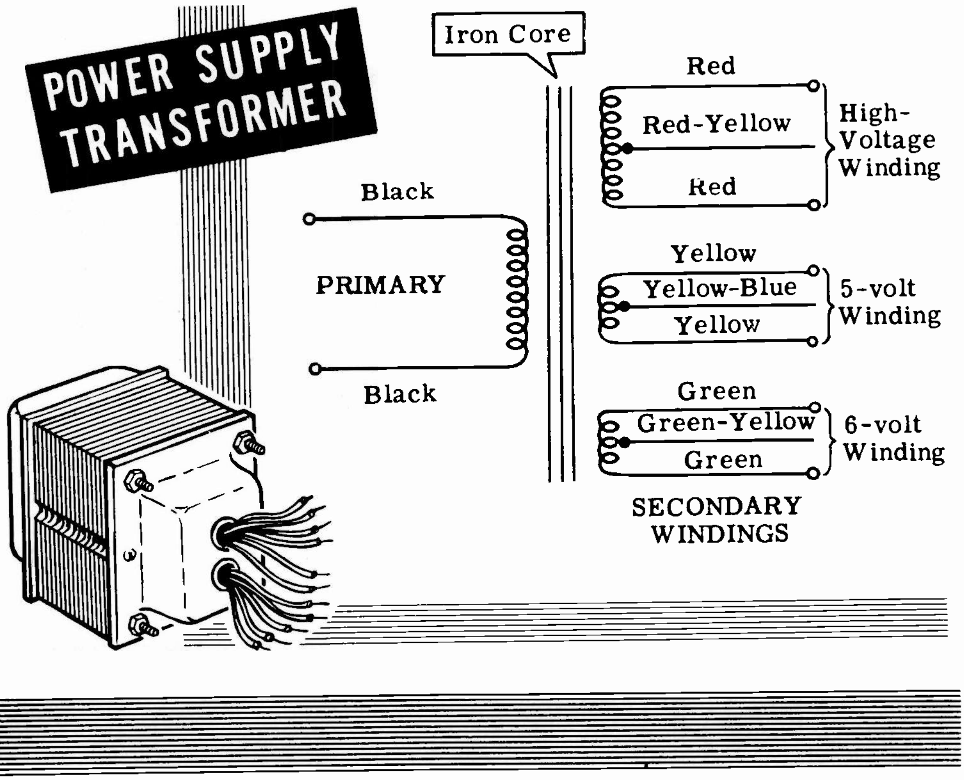
LAMINATED CORE CONSTRUCTION reduces Eddy Current and Power Loss

Hysteresis loss depends on the core material used. Each time the AC current reverses in the primary winding, the field in the core reverses its magnetic polarity. This field reversal requires a certain amount of power, resulting in a loss called "hysteresis loss." Some materials, such as silicon steel, change polarity easily, and when these materials are used as the core material, hysteresis loss is reduced to a minimum.

The Power Supply Transformer

Transformers are designed for many different uses and frequencies. The type of transformer you will probably be most concerned with is the power supply transformer. It is used to change the 117 volt 60 cycle power frequency to whatever 60 cycle voltage is needed to operate motors, lighting circuits and electronic equipment.

The illustration shows a typical power supply transformer for electronic equipment. You see that the secondary consists of three separate windings —each secondary winding supplying a different circuit with its required voltage. The multiple secondary eliminates the need for three separate transformers, saving cost, space and weight. The iron core is shown by the standard symbol. Each secondary has three connections. The middle connection is called the "center tap," and the voltage between the center tap and either outside connection is one half the total voltage across the winding.



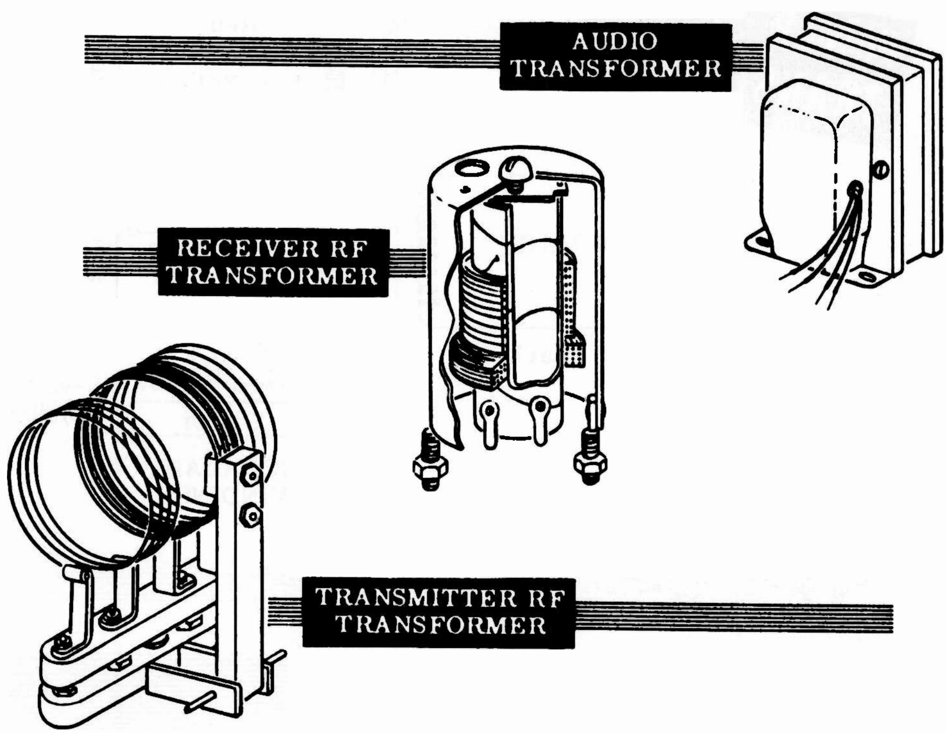
The number of turns shown in a schematic does not necessarily indicate whether the transformer is step-up or step-down. The windings are color-coded by the manufacturer, to indicate the separate secondary windings, their use and the way they are to be connected. The color-code shown is a standard one, but manufacturers may use other color-codes or may use numbers to indicate the proper connections.

Other Types of Transformers

In addition to power transformers, which operate at 60 cps (cycle per second), there are transformers designed to operate at different frequencies.

The audio transformer is designed to operate on the range of "audio" frequencies—those frequencies which are audible to the human ear—20 cps to 20,000 cps. The audio transformer has an iron core and is similar in appearance to the power transformer.

In receivers and transmitters, frequencies much higher than the audio range are used, and these frequencies are called "radio frequencies"—100,000 cps or 100 kilocycles (kc) and higher. Radio frequency (rf) transformers do not have iron cores because at such frequencies the core losses would be too great, and therefore rf transformers are "air core" transformers. The coils are wound on a non-magnetic form. The illustrations show a receiver rf transformer and a transmitter rf transformer. In the transmitter rf transformer, the windings are spaced far apart because of the high voltages used.



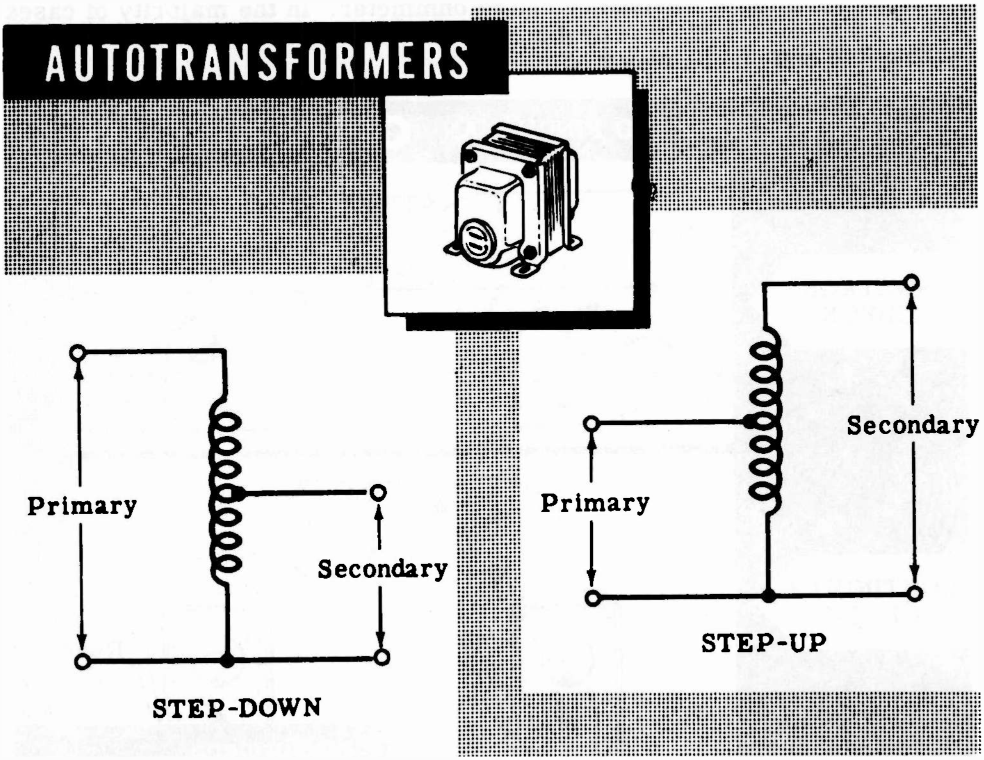
All these transformers have only one primary winding and are called "single phase" transformers. Other transformers, which operate from three AC voltages, are called "three phase" transformers. These transformers will be discussed in the section on alternators.

Autotransformers

The autotransformer differs from other transformers in that it has only one winding, rather than two or more as in ordinary transformers. Part of this winding is used for both primary and secondary, while the rest of the winding acts as either the primary or secondary exclusively, depending on whether the autotransformer is used to step down or step up the voltage.

A step-up autotransformer uses a portion of the total winding as the primary. AC current flow in this portion of the winding causes an expanding and collapsing field, which cuts across all of the coil turns and induces a higher voltage across the entire coil than that across the portion used as the primary. The end terminals of the coil then can be used as a secondary winding having a higher voltage than that of the primary section.

If the entire coil is used as the primary winding and only a portion is used for the secondary, the secondary voltage is less than that of the primary. When so connected, the autotransformer is used to step down voltage.

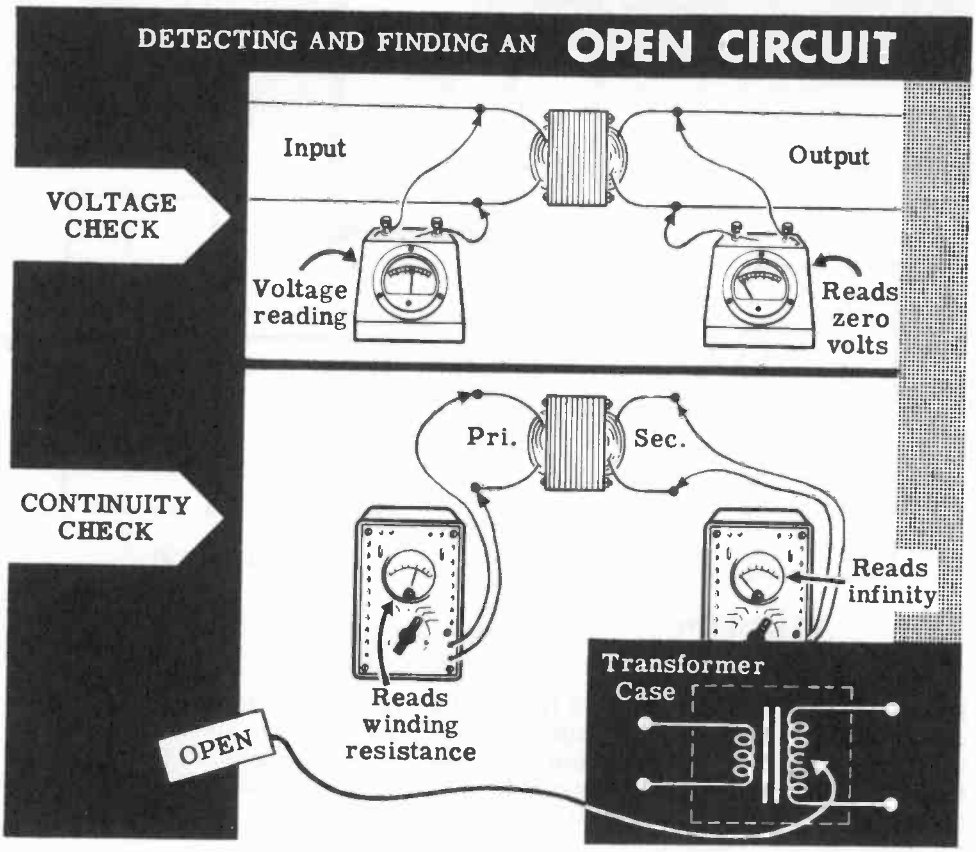


In the autotransformer, part of the winding is common to both the primary and secondary and carries both currents. Autotransformers require less wire since only one coil is used and they are less expensive than two-coil transformers. However, autotransformers do not isolate the primary and secondary circuits and cannot be used in many electrical and electronic circuits for this reason.

Troubleshooting

Since transformers are an essential part of the equipment you will work with, you should know how to test and locate troubles that develop in transformers. The three things that cause transformer failures are open windings, shorted windings, and grounds.

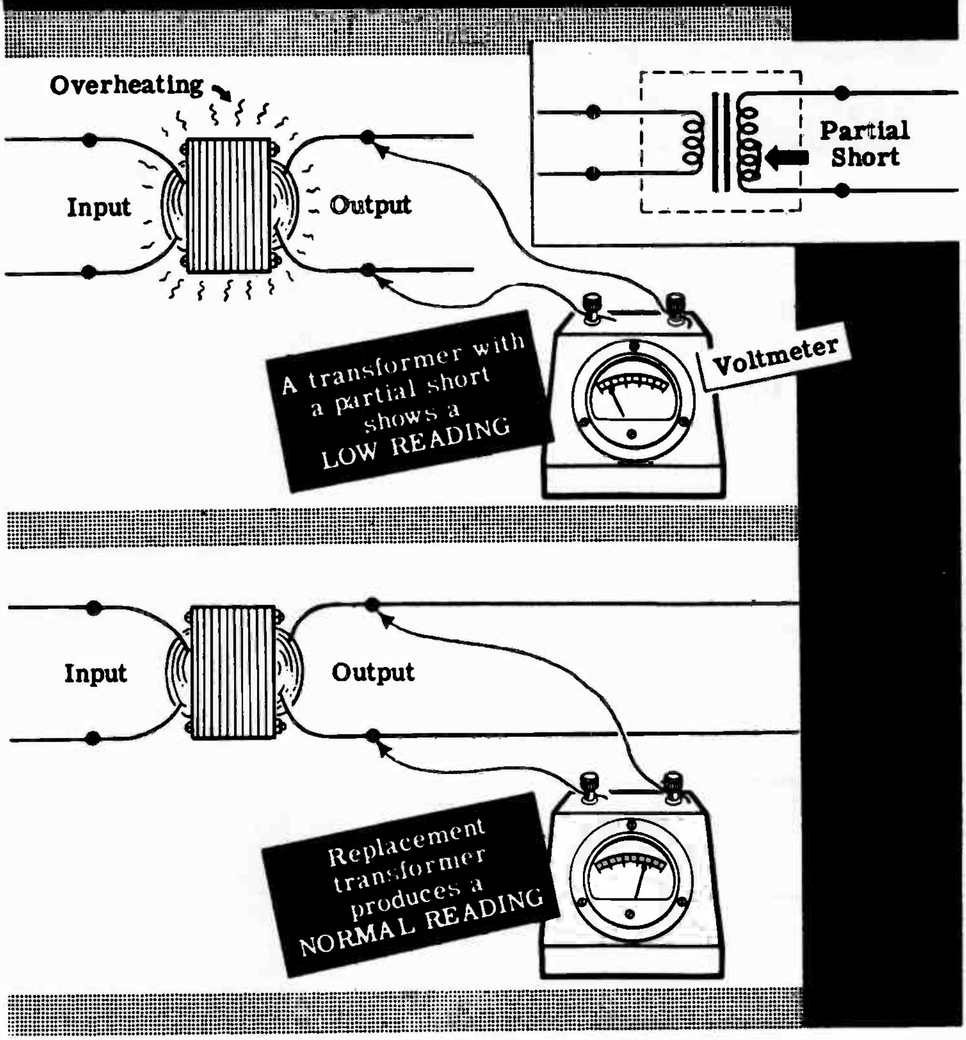
When one of the windings in a transformer develops an "open," no current can flow and the transformer will not deliver any output. The symptom of an open-circuited transformer is that the circuits which derive power from the transformer are dead. A check with an AC voltmeter across the transformer output terminals will show a reading of zero volts. A voltmeter check across the transformer input terminals shows that voltage is present. Since there is voltage at the input and no voltage at the output, you conclude that one of the windings is open. Next you check the transformer windings for continuity. After disconnecting all of the primary and secondary leads, each winding is checked for continuity, as indicated by a resistance reading taken with an ohmmeter. Continuity, (a continuous circuit) is indicated by a fairly low resistance reading, while the open winding will indicate an infinite resistance on the ohmmeter. In the majority of cases the transformer will have to be replaced, unless of course the break is accessible and can be repaired.



Troubleshooting (continued)

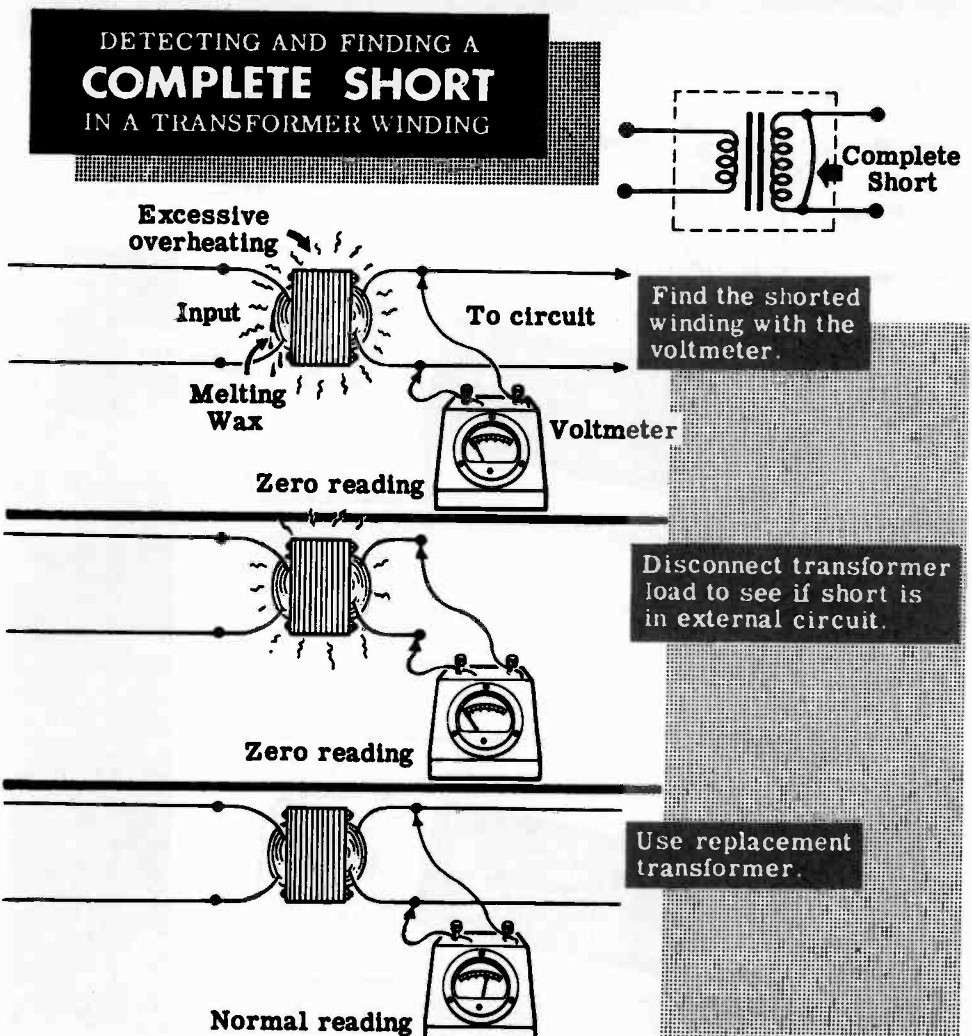
When a few turns of a secondary winding are shorted, the output voltage drops. The symptoms are that the transformer overheats due to the large circulating currents flowing in the shorted turns and the transformer output voltage is lower than it should be. The winding with the short gives a lower reading on the ohmmeter than normal. If the winding happens to be a low voltage winding, its normal resistance reading is so low that a few shorted turns cannot be detected by using an ordinary ohmmeter. In this case, a sure way to tell if the transformer is bad is to replace it with another transformer. If the replacement transformer operates satisfactorily it should be used and the original transformer repaired or discarded, depending upon its size and type.

DETECTING AND FINDING A **PARTIAL SHORT**



Troubleshooting (continued)

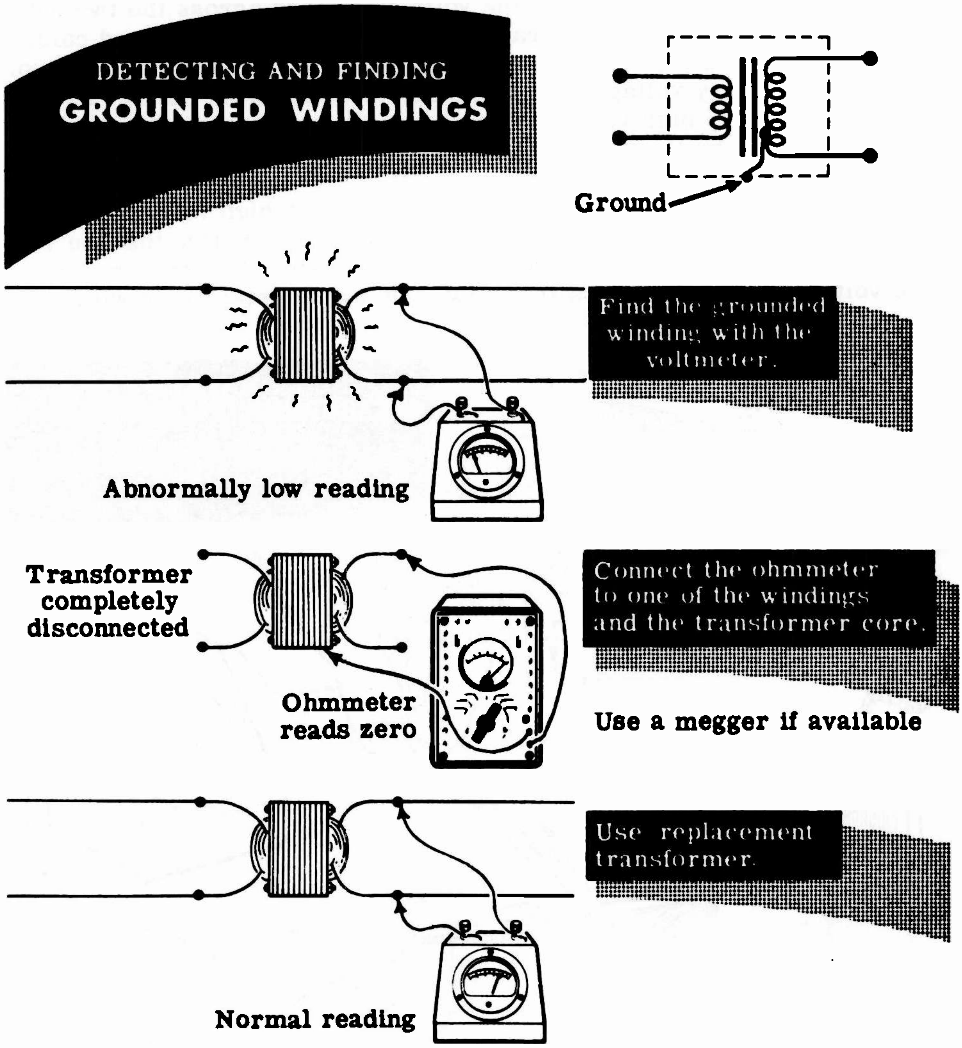
Sometimes a winding has a complete short across it. Again, one of the symptoms is excessive overheating of the transformer due to the very large circulating current. The heat often melts the wax inside the transformer, which you can detect quickly by the odor. Also, there will be no voltage output across the shorted winding and the circuit across the winding will be dead. In equipment which is fused, the heavy current flow will blow the fuse before the transformer is damaged completely. If the fuse does not blow, the shorted winding may burn out. The short may be in the external circuit connected to the winding or in the winding itself. The way to isolate the short is to disconnect the external circuit from the winding. If the voltage is normal with the external circuit disconnected the short is in the external circuit. If the voltage across the winding is still zero, it means the short is in the transformer and it will have to be replaced.



Troubleshooting (continued)

Sometimes the insulation at some point in the winding breaks and the wire becomes exposed. If the bare wire is at the outside of the winding, it may touch the inside of the transformer case, shorting the wire to the case and grounding the winding.

If a winding develops a ground, and a point in the external circuit connected to this winding is also grounded, part of the winding will be shorted out. The symptoms will be the same as those described for a shorted winding and the transformer will have to be replaced. You can check for a transformer ground by connecting the megger between one side of the winding in question and the transformer case, after all the transformer leads have been disconnected from the circuit. A zero or low reading on the megger shows that the winding is grounded.

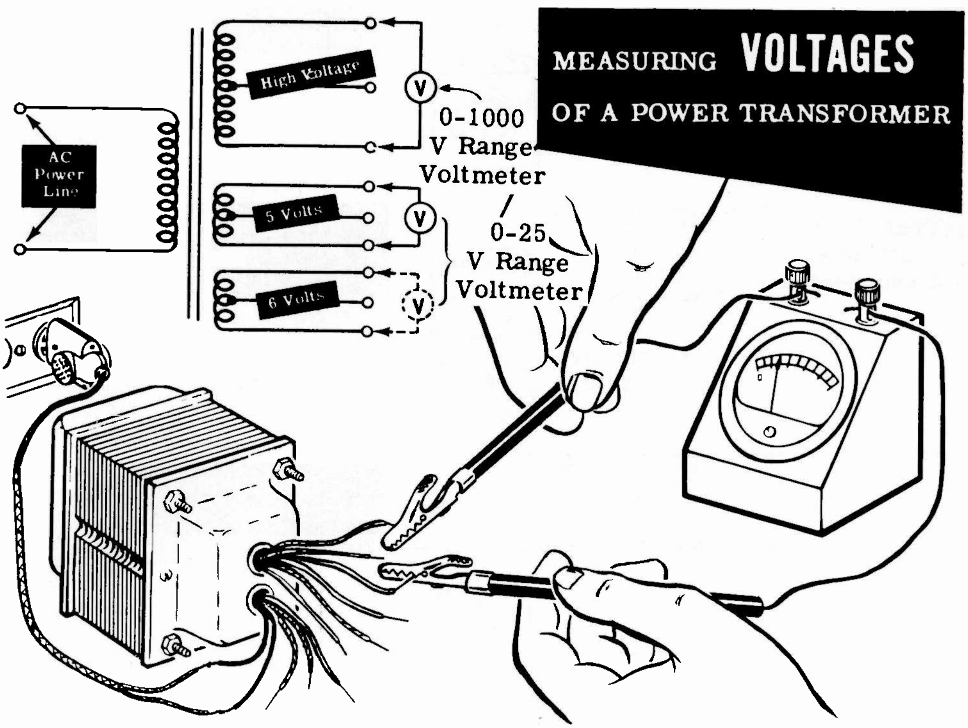


Demonstration—Voltage Measurements

To demonstrate power transformer action in stepping voltage up or down, the instructor uses a power transformer made up of one primary winding, and three secondary windings consisting of a step-up high voltage winding and two step-down low voltage windings, all center-tapped. See the schematic below.

The instructor carefully separates the winding leads to make certain none are touching each other or the case. Then he attaches a line cord to the primary leads. A 0-1000 volt range AC voltmeter is set up to take measurements. He plugs the line cord into the 110-volt socket and measures the AC voltage across the different transformer windings. With the voltmeter leads placed across the primary, the voltmeter reads 110 volts, the line voltage. Next, he places the voltmeter leads across the two outside high voltage leads. These leads can be identified by their red color. Notice that the voltmeter reads a very high voltage. Knowing the high voltage and the primary voltage, you can easily determine the turns ratio between the secondary high voltage winding and the primary by dividing the secondary voltage by the primary voltage.

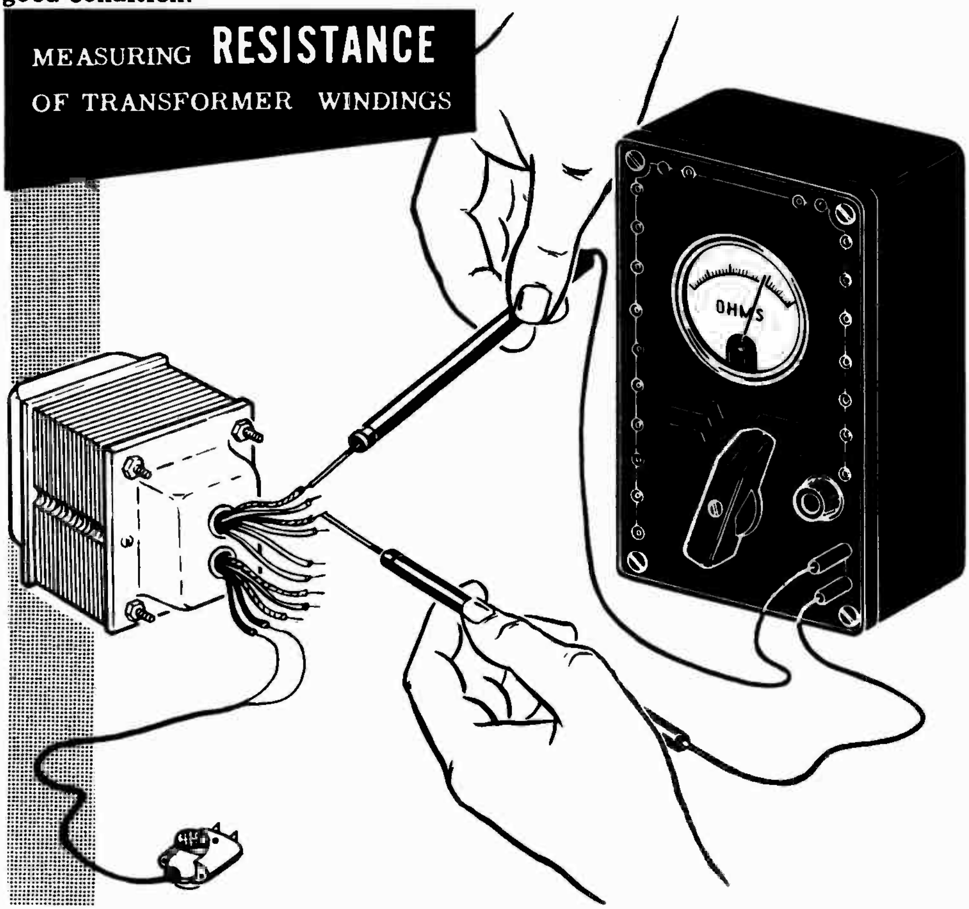
Now the instructor measures the voltage between the high voltage center tap and first one and then the other high voltage lead. Notice that the voltage is exactly half that across the outside terminals. He repeats the above voltage measurements with the two low voltage step-down windings.



Demonstration—Resistance Measurements

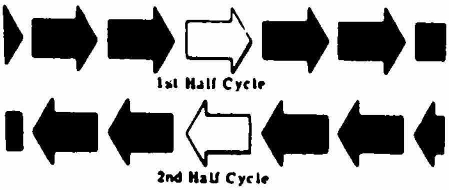
Next the instructor measures the resistance of the various windings of the power transformer with an ohmmeter. (Caution: This reading must be taken with no power applied to the transformer, otherwise the ohmmeter would be damaged.) The ohmmeter leads are first placed across the primary winding, then across the entire high voltage secondary. Observe that the resistance of the high voltage winding is much higher than the resistance of the primary. This is because the high voltage winding has many more turns than the primary winding. As the instructor measures the resistance from the center tap of the high voltage winding to either end you see that resistance equals one-half that of the full winding.

Next the ohmmeter leads are placed across the two low voltage windings. Observe that the ohmmeter reads practically zero ohms for both windings. This is because these windings have few turns of comparatively large diameter wire. You could not tell if these windings were shorted by means of a resistance measurement. The only way to check the low voltage windings is to measure their output voltage with all circuits disconnected from them. If the voltage readings are normal, the windings are probably in good condition.

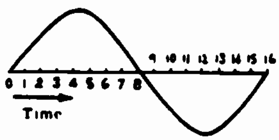


Review of AC Circuits

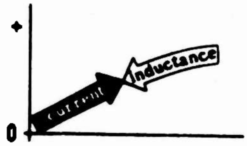
You have learned about AC circuits, and have investigated the various factors which affect AC current flow. This review sums up all these factors, and gives you the opportunity to check yourself on each point.



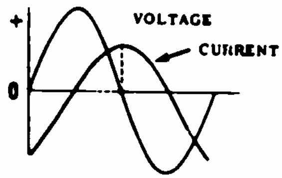
ALTERNATING CURRENT — Current flow which reverses its direction at regular intervals and is constantly changing in magnitude.



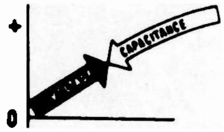
SINE WAVE — A continuous curve of all the instantaneous values of an AC current or voltage.



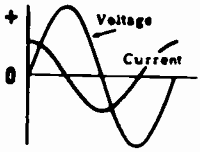
INDUCTANCE — The property of a circuit which opposes any change in the current flow.



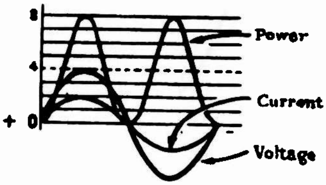
INDUCTIVE REACTANCE — The action of inductance in opposing the flow of AC current and in causing the current to lag the voltage.



CAPACITANCE — The property of a circuit which opposes any change in the circuit voltage.

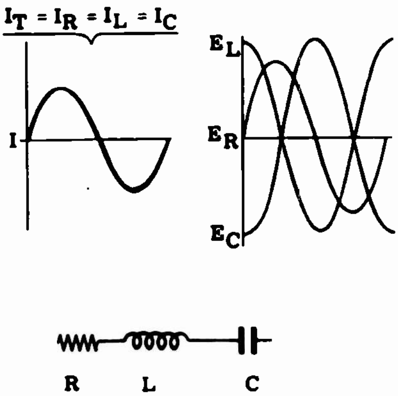


CAPACITIVE REACTANCE — The action of capacitance in opposing the flow of AC current and in causing the current to lead the voltage.



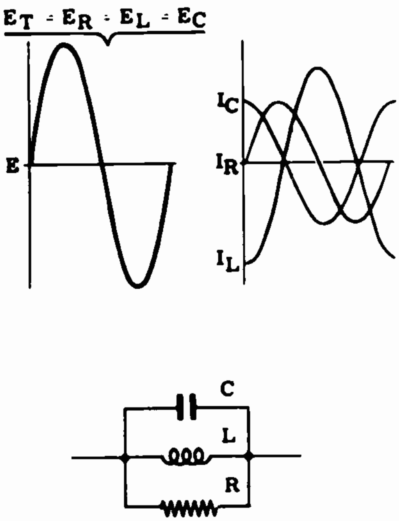
POWER — In AC circuits true power is equal to EI x cos θ, where the power factor (cos θ) is equal to the ratio of the resistance divided by the impedance ($\frac{R}{Z}$).

Review of AC Circuits (continued)



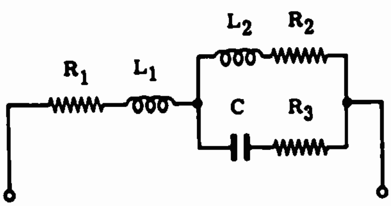
AC SERIES CIRCUIT — The current is the same in all parts of the circuit, while the voltage divides across the circuit and differs in phase.

SERIES RESONANCE — When X_L and X_C are equal, a series circuit is at resonance having minimum impedance and maximum current.



AC PARALLEL CIRCUIT — The voltage is the same across each parallel branch while the current divides to flow through the various branches, with the branch currents differing in phase and amplitude.

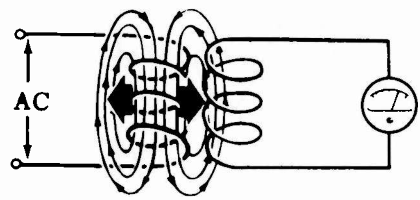
PARALLEL RESONANCE — When X_L and X_C are equal, a parallel circuit is at resonance, having maximum impedance and minimum line current. At resonance, the circulating current is greater than the line current.



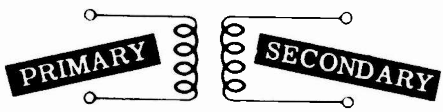
AC SERIES-PARALLEL CIRCUIT — The current divides to flow through the parallel branches while the voltage divides across series parts of the circuit. Voltage and current phase relationships for each part of the circuit depend on whether the part is made up of resistance, inductance or capacitance.

Review

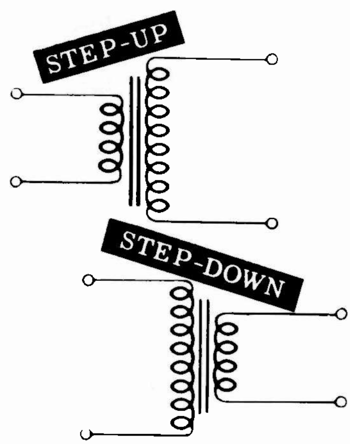
Here is a review of the most important points about the transformer.



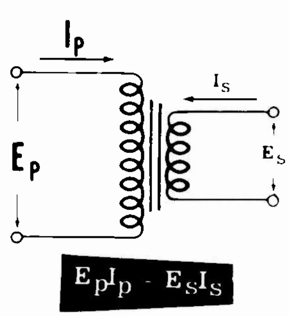
TRANSFORMER ACTION—The method of transferring electrical energy from one coil to another by means of an alternating magnetic field. The coils are not physically connected. They are only magnetically coupled. The alternating magnetic field generated in one coil cuts through the turns of another coil and generates a voltage in that coil.



PRIMARY AND SECONDARY WINDINGS—The coil which generates the alternating magnetic field is called the "primary." The coil in which a voltage is induced by the alternating magnetic field is called the "secondary." The voltage induced in the secondary depends upon the turns ratio between the secondary and primary.



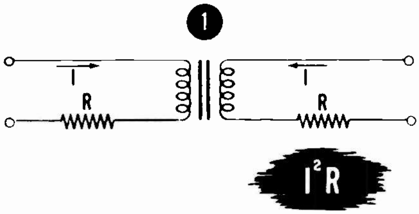
STEP-UP AND STEP-DOWN TRANSFORMER—If there are more turns in the secondary than in the primary, the transformer is "step-up," and the secondary voltage will be higher than the primary voltage. If there are fewer turns in the secondary than in the primary, the transformer is "step-down," and the secondary voltage will be lower than the primary voltage. The ratio of the secondary voltage to the primary voltage is equal to the turns ratio.

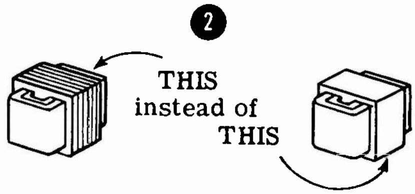


PRIMARY AND SECONDARY CURRENT—The power delivered by a transformer is equal to the power put into the transformer, assuming 100 percent efficiency. Stating this in terms of a formula, $E_pI_p = E_sI_s$. From this formula it can be seen that, if the transformer steps up the voltage, it will reduce the current. In other words, the transformer changes the current in the opposite direction to the change in voltage.

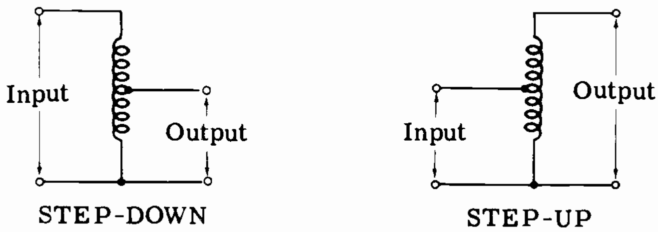
Review (continued)

TRANSFORMER LOSSES: Transformers designed for low frequencies are wound around iron cores to offer a low resistance path for the magnetic lines of force. This allows for a maximum amount of coupling between the primary magnetic field and the secondary winding, with the result that energy is transferred to the secondary at low loss. Transformers do suffer losses which are of three types: (1) the I^2R loss incurred by current flowing through the resistance of the windings, (2) eddy current losses caused by induction currents in the core material and (3) hysteresis losses caused by the reversal of core polarity each time the magnetic field reverses.





AUTOTRANSFORMERS: In addition to the two winding transformers, there are single winding transformers called "autotransformers." Electrical energy is transferred from one part of the coil to another part of the coil by magnetic induction. The voltage and currents vary in the same manner as in the two winding transformers.



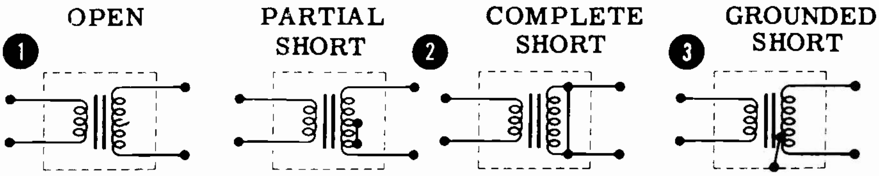
TRANSFORMER TROUBLES:

1. One of the windings can develop an open circuit.

2. Part or all of one winding can become shorted.

3. A ground can develop.

In troubleshooting a transformer, a voltmeter and ohmmeter are used to locate the trouble. If a transformer is defective, it usually must be replaced.



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