CREI

SPECIALIZED TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

POWER CONSUMPTION IN ELECTRICAL CIRCUITS

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POWER CONSUMPTION IN ELECTRICAL CIRCUITS

FOREWORD

The high level of our present civilization is based primarily on the large amounts of energy that are at our disposal, particularly in electrical form. The slaves of limited power in the days of ancient Greece have been replaced by mechanical horses: motors, engines, jet propulsion, and the like, and labor-saving devices are legion in number.

It is therefore clear that the calculation of power, and particularly power consumed in electrical circuits, is of fundamental importance to everybody, and particularly the electrical engineer and radioman. Power consumed may refer to power usefully expended, or it may refer to power unavoidably wasted; the calculations are the same in either case.

This assignment deals not only with power calculations, but also with such related matters as the measurement of circuit resistance, the losses in circuits, particularly at radio frequencies, and that all-important matter of efficiency: the ratio of power output to power input.

The last two topics, namely circuit losses and efficiency, are also of importance for reasons other than purely economic: the selectivity of a tuned circuit, or the difference between the wattmeter reading and the volt-ampere product determine the performance of a device aside from its evaluation on a power basis.

The concept of resistance is itself closely tied in with power consumption. An antenna actually radiates electromagnetic energy into space for useful purposes, yet such departure of energy from the transmitter can be looked upon as a loss similar to that in the cooling water of the transmitter tubes. As a result, we have the concept of antenna *radiation* resistance; the useful power radiated may be computed on the same basis as power unavoidably wasted as heat.

It is clear from the foregoing that this assignment is of basic importance; further topics in radio engineering cannot be developed until this assignment has been mastered. You should study it with this thought in mind.

E. H. Rietzke,
President.

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SCOPE OF ASSIGNMENT

This assignment deals with the calculation of the electrical power consumed in various forms of electrical circuits. Since power is consumed in the resistive portions of a circuit, the manner in which various pieces of equipment, such as coils, capacitors, etc. absorb power is discussed first, and then the method of measuring resistance is discussed, including r-f resistance.

Since the power consumed in useful resistances-such as the radiation resistance of an antenna-is but part of the total power consumed, the question of efficiency naturally arises, and the calculation of this factor is therefore discussed next.

Next the concept of power factor, which is used in the analysis of a-c circuits, is discussed, and it is shown how it effects the reading of a wattmeter. Finally the application of these principles is taken up with regard to losses in a-c circuits, with particular reference to the r-f losses in a circuit, since these are over and above the resistance losses incurred at d-c and low a-c frequencies.

FUNDAMENTAL CONSIDERATIONS

DEFINITION OF POWER.—Power is defined as, "The time rate at which work is done". P = W/t where W is work in joules (10^7 ergs), t is time in seconds, and P = power in watts. Power may also be expressed in horsepower; one horse-power = 33,000 foot-pounds/minute = 746 watts. 1000 watts = 1 kilowatt. In all of these definitions time enters as a factor so that power represents not a given amount of work but *the rate at which work is done.*

As power is expended work is done. In the design of machinery or power operated equipment of any kind, a primary object is to have the maximum possible expenditure of power in *useful* work and the minimum in *non-useful* work. For example, consider the operation of an electric motor which drives some piece of machinery which represents the motor load. The ideal condition would be to have all of the electric power delivered to the motor converted into mechanical power at the load. This ideal condition is impossible to attain because of unavoidable *power loss.* Some of the loss is mechanical, due to friction in the bearings and wind resistance as the rotor section of the motor rotates at high speed. Other power loss is electrical and is indicated by the heat developed in the motor windings. Still other power loss is magnetic due to the variations of the magnetic field in the steel frame, pole pieces and rotor core. The efficiency of a typical medium size electric motor as used in radio, defined as the ratio of the useful power/total power, may be in the order of 85 per cent.

POWER LOSSES.—Large transformers used in higher power radio transmitters are among the most efficient pieces of apparatus. The operating efficiency may be in the order of 97 or 98 per cent. Since there are no moving parts there is no mechanical power expenditure, the only power losses being electrical.

A radio transmitter is probably

one of the most inefficient converters of power used commercially. The only useful power obtained from a radio transmitter is *the energy actually radiated in space from the antenna.* All other energy is dissipated in the apparatus in the form of heat. The ratio of antenna power to power input varies over a wide range, being greater in high power transmitters and smaller in low power transmitters. In one police U.H.F. automobile radio transmitter, the carrier power output is 5 watts as compared with a power input to the transmitter of 200 watts, an efficiency of 2.5 per cent. In a 5 K2 broadcast transmitter which also can be operated at 1 KW output, the input power for 1 KW out is 13 KW, slightly under 8 per cent efficient; for 5 KW output, the power input is 28 KW, efficiency just under 18 per cent. In the case of one 500 KW transmitter, the approximate power input is 2000 KW, with overall efficiency of almost 25 per cent. A more modern design of 5 KW transmitter produces carrier output of 5 KW with power input of 15 KW, efficiency being equal to 33 per cent. In all of these cases, the real power radiation from the antenna is less than the rated power delivered to the antenna by the transmitter, so that all efficiencies listed above are subject to some reduction, the amount of the reduction being a function of the antenna design and construction.

Before it is possible to analyze the sources of power loss in radio apparatus and take steps in design to improve the operating efficiency, it is necessary to understand just when and how power is dissipated and how to measure or calculate the power expended.

CONVERSION INTO HEAT.—Power is expended in a circuit *only* in overcoming the resistance of the circuit. The power used in building up a magnetic field around an inductance is returned to the circuit when the field collapses back on the conductor; the power used in charging a capacitor is returned to the circuit when the capacitor discharges. Thus, as shown in an earlier discussion of the KVA/KW ratio, it is possible to have quite large currents and voltages in radio frequency circuits with quite small power dissipation.

The heat produced in the turns of an inductance coil due to electronic collisions, that is, in the *resistance* of the conductor when the current is flowing through the turns to build up the magnetic field or in the collapse of the magnetic field, is the result of power dissipation. This expenditure of power is a total loss in the circuit as it is not returnable in a useful form.

In a similar manner, the heat produced in the dielectric of a capacitor due to the rapid displacements of electrons, requires the expenditure of power and this power also is a total loss to the circuit electrically.

The power expended in a direct current circuit is equal to the product of the current times the voltage, P = EI. This is due to the fact that in a d.c. circuit the voltage has only the resistance of the conductor to overcome, and all of the voltage is used up in forcing the current through the resistance of the circuit, R being the only opposition to current flow.

In an alternating current circuit composed entirely of resistance, i.e. one having no inductive or capacitive reactance, the only opposition to current flow is still the circuit resistance. In such a circuit the equation, P = EI, still holds true, E being the effective (R. M. S.) value of voltage and I the effective (R.M.S.) current.

The condition of a circuit containing only resistance is the condition existing in radio frequency circuits operated at resonance, where the inductive reactance exactly counteracts the capacitive reactance, the total reactance being, therefore, equal to zero and the resistance making up the total opposition to current flow. Such a circuit is said to be operating at zero phase angle or unity power factor and the voltage and the resultant current are in phase.

If a voltmeter could be connected across a series resonant radio frequency circuit and an ammeter connected in series in the circuit, the power expended could be measured just as in any low frequency power circuit.

It is a simple matter to connect a radio frequency ammeter in series in the circuit, but if an ordinary voltmeter is connected across the circuit, the condition of resonance will no longer exist due to the inductance and capacity of the voltmeter. Also, with a circuit such as an antenna there is no practical method of connecting a voltmeter across the circuit. (In certain types of resonant circuits it is possible to measure the voltage by means of a vacuum tube voltmeter). In radio frequency circuits the values of L, C and R are distributed throughout the circuit and measurements with conventional low frequency type instruments are not feasible.

It is desirable and usually necessary, therefore, to have some method of determining the power expended in the circuit, without the use of a voltmeter. Returning to the original equation, P = EI.

According to Ohm's Law, E = IR.

Replacing E in the original equation with its equivalent as determined from Ohm's Law,

$$P = EI$$
$$P = (IR)I$$
$$P = I^2R$$

The equation for power is now expressed in terms of current and resistance instead of current and voltage. The current in any radio frequency circuit may be measured by connecting a radio frequency ammeter in series in the circuit, and it is a comparatively simple matter to measure the radio frequency resistance of most circuits. Then, knowing the current and the resistance, the power may be calculated from the product of the current squared times the measured resistance, $P = I^2R$.

MEASUREMENT OF CIRCUIT RESISTANCE.—The radio frequency resistance of a circuit operated at resonance may be measured with a fair degree of accuracy by means of the "half-deflection" method. This method may be used to measure the resistance of any purely resistance circuit where the only meter available or practical to use is an ammeter. The exception to this is in the case of certain types of circuits at very high radio frequencies—in the order of several megacycles—where the change in circuit constants due to an inserted resistance may vary the current distribution throughout the circuit considerably. One method of calculating the approximate power expended in such a circuit will be discussed later in this lesson. At low and intermediate radio frequencies a fair degree of accuracy may be obtained in R.F. resistance measurements by means of the "half-deflection" method.

Suppose it is desired to measure the radio frequency resistance of a circuit as shown in Figure 1.

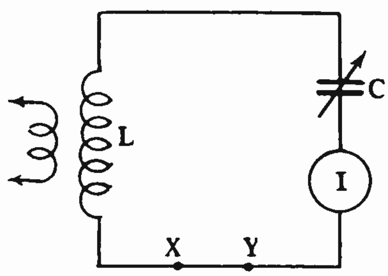


Fig. 1.—Resonance circuit at a frequency.

Since Ohm's Law applies to circuits operated at resonance, and since with a constant source of power a reasonably constant voltage across the circuit may be assumed, then if the resistance of the circuit were to be doubled, the current would be decreased to exactly one-half its former value.

Assume that the circuit contains an unknown amount of resistance and that the power input is adjusted so that the ammeter (I) indicates two amperes. Connect a calibrated variable resistance between points X and y and adjust the resistance to the point where the current is decreased to one ampere. Since the current has been decreased to one-half its former value, the resistance must have been doubled. To double any amount it is necessary to add an amount equal to the original. Therefore, to decrease the current from two amperes to one ampere, there must have been added a value of resistance *equal to the resistance already present in the circuit.* If the added resistance is 8 ohms, then the original R.F. resistance of the circuit is 8 ohms.

To apply this practically to the circuit as shown in Figure 1, connect the calibrated variable resistance between points x and v, as shown in Figure 2. With the variable resistance adjusted to a zero

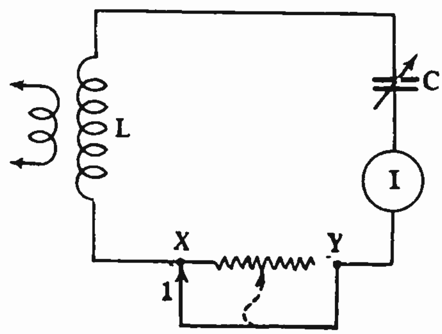


Fig. 2.—Half deflection method of measuring r-f resistance.

value as at point 1, the circuit is turned to resonance and the exact reading of the ammeter noted. The variable resistance arm is then moved to the right, connecting additional resistance into the circuit. Resistance is added until the ammeter reading is decreased to exactly one-half its former value. Then if the applied voltage has not changed, or the circuit detuned, the resistance of the circuit will equal the value of the known inserted resistance. If the inserted resistance equals 7.4 ohms the normal resistance of the circuit also must equal 7.4 ohms.

In order to avoid detuning the circuit appreciably when adding resistance, a good non-inductive resistance should be used. There is no such thing as a perfectly non-inductive resistance, so when working with high frequency circuits where a very small change in circuit L or C will cause an appreciable change in frequency, the circuit should be kept at exact resonance by slightly re-adjusting the variable capacitor for each variation of resistance. The adjustment should be just enough to keep the indication of the ammeter at the highest possible value with the additional resistance in the circuit. This will of course indicate a condition of circuit resonance.

If the measurement is to be accurate the applied voltage must be kept as nearly constant as possible during the entire measurement. This may be checked by quickly cutting out the inserted resistance by moving the variable contact back to position 1 immediately after noting the reading on position 2. If the ammeter reading is the same as its original reading before the resistance was inserted it may be assumed that the input power remained reasonably constant during the measurement, so far as power line variations are concerned. The principal source of inaccuracy in radio frequency resistance measurements where the power supply is a vacuum tube circuit—the practically universal condition—is the change in tube power output with variation of load. This may be minimized by using an adequate power supply, weak coupling to the circuit being measured, and a radio frequency millammeter instead of an ammeter. The weaker the coupling and the smaller the measured circuit power, the greater the accuracy.

A greater degree of accuracy may be obtained by making several measurements, changing the applied power each time to obtain a different ammeter reading at the beginning of each measurement. The measured circuit resistance should be the same in all the measurements, but there usually will be slight changes of power and errors of reading so that the values of resistance as measured may differ slightly. An average of all of the measured values will approach very closely the true resistance of the circuit. A somewhat more accurate method of measuring radio frequency resistance used extensively in laboratories, will be discussed in a later lesson.

CALCULATIONS

CALCULATION OF POWER AND EFFICIENCY.—After determining the resistance of a circuit it is a simple matter to calculate the power expended in that circuit. The circuit is adjusted to the desired operating condition and the current is indicated by the ammeter. Assume that the circuit resistance is found to be 7 ohms and the current is 10 amperes. Using the power equation,

$$P = I^2R$$

$$P = 10^2 \times 7 = 700 \text{ watts}$$

The radio engineer, technician and operator must thoroughly understand the difference between circuit current and circuit power expenditure, particularly as these terms refer to the antenna power of a radio transmitter. It is useless to compare two transmitters on the basis of their antenna currents because a specified antenna current can represent high or low power, depending upon the resistance of the antenna. The resistance of the antenna depends upon a number of factors, including the operating frequency, type of ground system, shape, dimensions, and even in some cases surrounding structures. In general, assuming equally good design in all cases, the resistance of an antenna increases with frequency because, as the frequency is increased, the proportion of the total electric and magnetic field energy around the antenna that is isolated in space by the radiation process increases.

For example, at a very low frequency transmitter in a shore station installation (assume frequencies in the order of 10 to 30 KC/s) the antenna resistance may be in the order of a fraction of an ohm. In a 500 KC/s ship-board installation, typical antenna resistance may be in the order of 6 to 10 ohms. In broadcasting, the antenna resistance may be anywhere from 15 to 20 ohms in the case of a .25 λ or shorter tower to approximately 70 ohms in the case of a well-designed .5 λ vertical tower.

The expenditure of power by radiation and the manner in which the antenna design enters into the radiation resistance are beyond the scope of this discussion. These factors will be discussed in considerable detail in later assignments.

Since, for a given circuit current, the power is directly proportional to R, ($P = I^2R$), the antenna resistance is an extremely important factor. Consider the case of two transmitting antennas in which, in both antennas, the R.F. ammeter indicate 20 amperes. One antenna has resistance of 10 ohms, the other 70 ohms.

$$P = I^2R = 20^2 \times 10 = 4000 \text{ watts} = 4KW$$

$$P = I^2R = 20^2 \times 70 = 28000 \text{ watts} = 28KW$$

The power delivered by the transmitter to the higher-resistance antenna is seven times greater than that of the lower resistance antenna, although both antenna ammeters indicate the same current.

Figure 3 shows the method of connecting the variable calibrated resistance to measure the resistance of an antenna. The precautions and procedure in this measurement are the same as in the measurement of the resistance of the circuit shown in Figures 1 and 2.

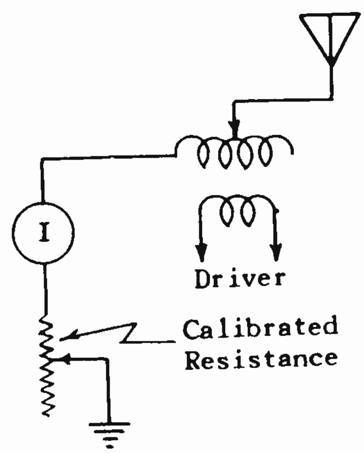


Fig. 3.—**Measuring r-f resistance of an antenna.**

A.C. POWER CIRCUITS.—In power circuits, (not radio frequency circuits at resonance), it is very seldom that the condition of "no reactance" is encountered. The various loads represented by motors, transformers, etc., possess inductance and resistance and the current in such a circuit is equal to E/Z where $Z = \sqrt{R^2 + X^2}$. In such a circuit the current lags the voltage and part of the total voltage is used up in forcing the current through the reactance, the remainder of the voltage being used in overcoming the resistance of the circuit.

$$E_t = \sqrt{E_r^2 + E_x^2}.$$

While voltage and power are necessary to force the current through the inductance to build up a magnetic field around the coil, *no power is expended in this operation because the magnetic field, when it collapses, returns power back into the circuit in amount equal to the power taken to build up the field.*

The product of the R.M.S. voltage, as indicated by a voltmeter, times the R.M.S. current, as indicated by an ammeter, does not, therefore, equal the power expended in the circuit when the circuit possesses reactance and the current and voltage are not in phase.

The R.M.S. voltage is divided into two components, one of the components forcing the current through the resistance of the circuit, the other component being used to force the current through the reactance of the same circuit. The vector *sum* of the two components of voltage equals the effective voltage of the source of supply.

The current is the same in all parts of a series circuit but the voltage forcing the current through the circuit is distributed, part being used in forcing the current through the resistance and part in overcoming the reactive opposition.

If the reactance is inductive the effect of the reactance is to tend to cause a current lag of ninety degrees. The effect of the resistance is to tend to keep the current and voltage in phase. But the current in all parts of the circuit at any instant must be the same; therefore the voltage across the resistive component of the impedance must be in phase with the current, and the voltage across the reactive component must be ninety degrees out of phase with the same current. If the reactance is inductive, the reactive component of voltage will LEAD the current by ninety degrees. Under this condition the current, while it is the same in all parts of the circuit, will be in phase with the resistive component of voltage while it will lag ninety degrees behind the reactive component of voltage.

This is shown in Figure 4. If the resistance and inductance are considered as non-inductive resistance in series with non-resistive inductance, and the inductive reactance is equal to the resistance, then the voltage drop across the inductance will equal the voltage drop across the resistance and the two voltages will act on the common current at angles separated by ninety degrees. The alternator voltage, E, will be the vector sum of E_r and E_L and therefore,

$$E = \sqrt{E_r^2 + E_L^2}.$$

Since $X_L = R$, the resulting voltage will be forty-five degrees ahead of the current and the current will be said to lag the voltage by forty-five degrees.

POWER CALCULATIONS IN AC CIRCUITS.—Of the two components of voltage, only the resistive component is causing the expenditure of power. The power used by the reactive component when the field is expanding as the current increases during the alternation, is returned to the circuit by the collapsing magnetic field when the current decreases and is, therefore, not expended. The power used up in forcing the current through the resistance is converted into heat and is, therefore, expended. The power expended in this circuit is equal to IE_r.

But $E_r = E \cos \theta$ and θ is equal to the angular phase difference between the current and voltage. Therefore, in a circuit possessing both reactance and resistance the power consumption may be expressed as,

$$P = EI \cos \theta$$

Cosine θ multiplied by 100 is called the POWER FACTOR of the circuit. In the example about $\theta = 45°$. $\cos 45° = .707$. The power factor of the circuit expressed in percentage is $PF = .707 \times 100 = 70.7$ per cent. The power in an A.C. circuit may be expressed as the current times the voltage times the POWER FACTOR written as a decimal:

$$P = E \cdot I \cdot PF.$$

From this relationship, it is possible to determine the phase angle if the voltage, current and power are known. The voltage is indicated by the voltmeter, the current is taken from the reading of the ammeter, and the power expended is shown by the wattmeter.

For example: Meter readings on the A.C. power distribution board of a radio transmitter are as follows: Voltmeter, 440 volts; Ammeter, 27.4

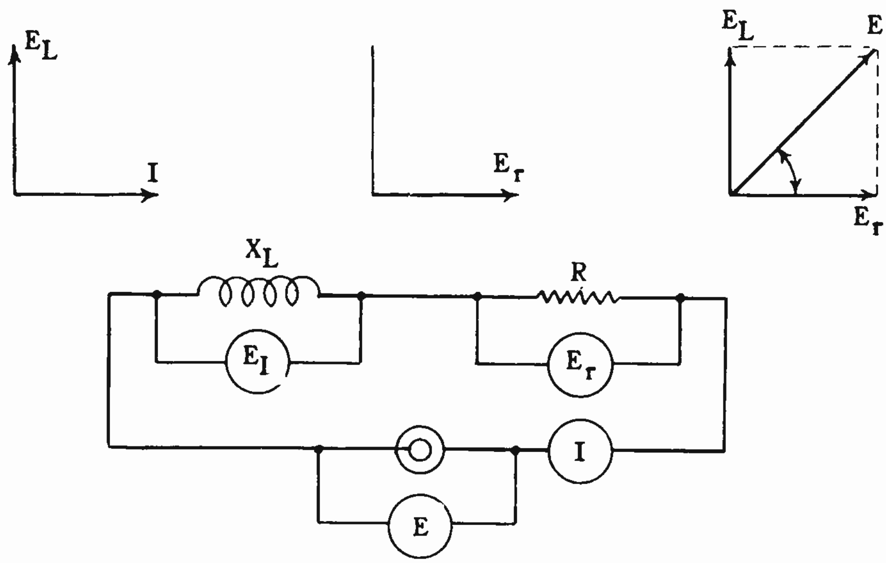


Fig. 4.—Phase relation between voltage and current in a series LR circuit.

amperes; Wattmeter, 11 KW. To find power factor and angle of current lag,

$$PF = 100 \text{ Cos } \theta$$

$$PF = \frac{P}{EI} \cdot 100 = \frac{11,000 \times 100}{440 \times 27.5}$$

$$= \frac{1,100,000}{12,100} = 90.0 \text{ per cent.}$$

$$\text{Cos } \theta = .909$$

$$\theta = \text{Cos}^{-1}\ .909 = 24°38'\ \text{lag.}$$

In this circuit the true power used up in performing work of some kind—radiated energy, filament heating, plate dissipation, etc.—is 11 KW as indicated by the wattmeter; the apparent power, as indicated by the product of the voltmeter and ammeter readings, is 12.1 KW. The power factor is 90.9 per cent and the current lags the voltage by an angle of 24°38′.

How is it known that θ represents an angle of lag and not lead? There is nothing in any of the meter readings to determine this but an angle of current lead can be caused *only* by a capacitive load and a radio transmitter is not such a load. The power input circuit of such a transmitter consists of plate and filament transformers and the reactive component is inductive.

The real and apparent power will be identical when the circuit contains only resistance. In that case the current and voltage are in phase; θ = 0° and Cos θ = 1.

A wattmeter, which may be calibrated in either watts or kilowatts, is a meter which, by means of the reaction between current and voltage coils, integrates the real power consumption of a circuit over the A.C. cycle as distinguished from the apparent power which is the product of current times voltage. One of the windings has high resistance and is connected *across* the circuit as a voltmeter; the second winding has low resistance and is connected in series with the circuit as an ammeter. The connection of the current (I) and voltage (E) windings are shown schematically in Figure 5(b).

In Figure 5(b) the load is shown as simple resistance and it is assumed, that the reactance is negligible. The current, voltage and power curves for such a circuit are shown in Figure 5(a). Above the reference line E, I and P are assumed to be positive, below the line, negative. P = EI Cos θ. In this case E and I are in phase, θ = 0°, Cos 0° = 1 and P = EI. From elementary algebra, the product of numbers of *like* sign is positive. Hence, whether E and I are + or −, so long as the sign of both is the same their product, P, is +. Thus the power curve P, which is plotted as the product EI, is + on both alternations.

This is indicated on the wattmeter for the following reason. The wattmeter employs two coils, one fixed, the other movable; the fixed coil may be thought of as a field, the movable coil as an armature. Movement of the movable coil, and hence of the pointer, is due to the reaction between the magnetic fields of these two coils, just as in the case of the rotation of an electric motor. In a d.c. motor, if the connections to *both* field and armature are reversed, the direction of rotation is unchanged. Likewise in the wattmeter; if the polarity in *both* windings is reversed—as in the adjacent alternations of Figure 5(A) the direction of indication of the pointer is unchanged. Just as A.C.

Period 3. From 180° to 270° E is - and I is +.
Period 4. From 270° to 360° both E and I are -.

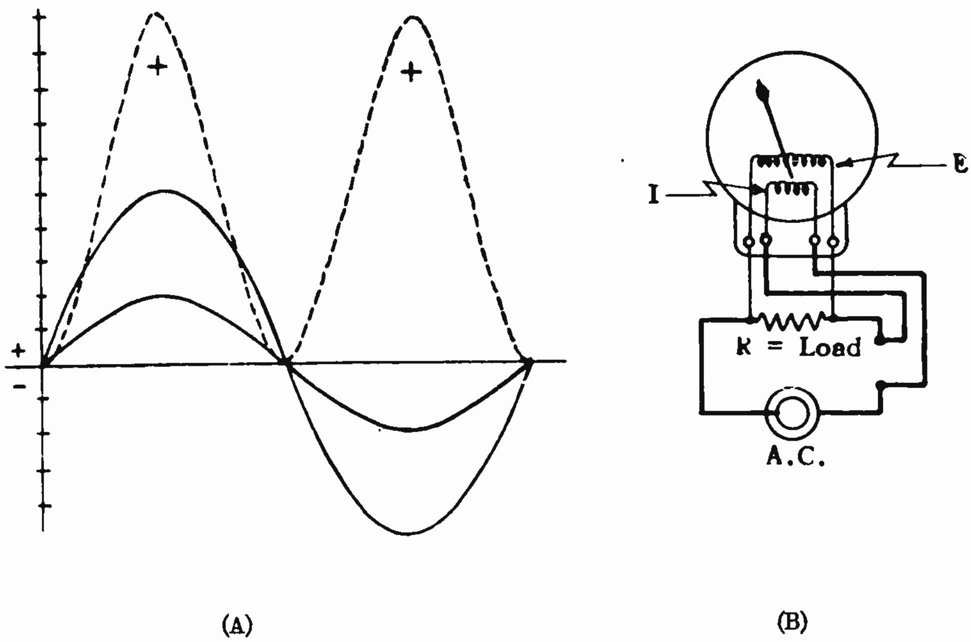


Fig. 5.—Power waveform for a pure resistance circuit and a schematic connection for a wattmeter.

voltmeters and ammeters indicate R.M.S. values of voltage and current, so does the wattmeter indicate the product of these R.M.S. values in terms of watts.

Now consider the operation of a wattmeter in a purely reactive circuit in which I lags E by 90°. The curves of E, I and P are shown in Figure 6. The situation is entirely different because now the signs of E and I are not always similar. If the cycle is divided into four periods:

Period 1. From 0° to 90° E is + and I is -.
Period 2. From 90° to 180° both E and I are +.

During Period 1, E and I have opposite signs, hence the product or power curve is -; during Period 2, the signs of both E and I are + and the power curve is +; during Period 3, E and I have unlike signs and the power curve is -; during Period 4, the signs of both E and I are - and the power curve is +. The power curve passes through zero each time either E or I is zero because at that instant the product EI is zero.

From the comparison of the wattmeter operation with that of a motor, it will be apparent that the wattmeter indicator will *try* to follow the power curve, changing its direction of indication as the power curve changes sign. Due to the frequency of the alternations and the damping of the moving parts, this is not mechanically possible and the indicator actually indicates the algebraic sum of the + and - components of power; that is, the reading of the wattmeter over a number of cycles, which represents the true power expended, is:

$$P = (+P) + (-P).$$

This is of course the difference obtained by subtracting the area under the -P curve from the area under the +P curve. Mathematically this would be done by integration; the integrating process is performed electromechanically by the wattmeter.

In the case of Figure 6 where, because of the 90° lag due to the *assumption of a perfectly reactive load* -P = +P, the areas under the two curves are identical and the wattmeter will indicate zero power consumption.

The significance of the positive and negative power curves is important. Power is required in building up the magnetic field around a coil and this power, which is employed in building up the field when E and I are operating in the same direction—that is, when the current is flowing under the influence of the applied voltage—is represented by the +P curve. *Note that during +P the current I is rising, in one direction or the other.* During this period the field is building up.

At the instant the field is expanded to maximum and the current ceases to rise, the absorption of power from the applied source becomes zero. At the next instant the decrease of current begins, the magnetic field starts to collapse cutting the turns in a direction opposite to that of the previously expanding field, *and the energy stored in the magnetic field is returned to the source.* This is re-

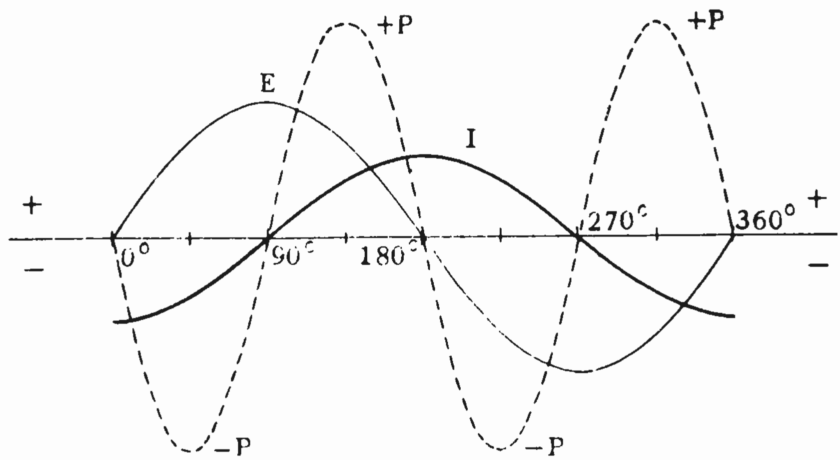


Fig. 6.—Power waveform for a pure reactive circuit.

presented by the negative power curves.

The *power expenditure* under the condition of Figure 6 will be zero because with no resistance losses the power returned by the collapsing magnetic field is equal to the power absorbed by the expanding field. This is shown mathematically as follows.

$$P = EI \cos \theta.$$

and

$$\cos \theta = 0.$$

Then

$$P = EI \cdot 0 = 0.$$

It is difficult to demonstrate the realness of the returned power in the -P curve of an inductive circuit because the effects are extremely rapid when applied power is removed from such a circuit. However, it can be done quite simply in a capacitive circuit. The E, I and P curves for a pure capacity reactive circuit resemble those of Figure 6 except that in the capacitive circuit I leads E by 90° instead of lagging. If a very low leakage high voltage condenser of large capacity rating if fully charged and the charging circuit then disconnected, the energy required to charge the capacitor will remain in the capacitor in the form of an electrostatic field. Such a charge may be stored in a really good capacitor for an appreciable period of time. If a discharge circuit of the proper resistance is connected across the capacitor, the energy can be used during discharge to operate a relay, light a small lamp, or perform similar work which will demonstrate, for a brief period, the actual power available in the stored energy.

In a capacitive circuit connected to an alternator the capacitor is continually charging and discharging, producing + and - power curves similar to those of Figure 6, +P occurring during the capacitor charge, -P during the discharge. In a purely reactive circuit (if such a circuit could be constructed) E and I could be large but a wattmeter, averaging out the + and - components, would indicate zero.

Now in practical power circuits the condition is different than in either Figure 5 or Figure 6. All reactances have resistance and most resistors have some reactance due to distributed L or C.

Consider an RL circuit in which $R = X_L$. In such a circuit, as previously shown, $\theta = 45°$ lag and $\cos \theta = .707$. Consider Figure 7 and take four periods similar to those for the curves of Figure 6.

Period 1. 0° to 45° E is + and I is -.

Period 2. 45° to 180° both E and I are +

Period 3. 180° to 225° E is - and I is +.

Period 4. 225° to 360° both E and I are -.

Mathematically the relation is the same as for Figure 6. The true power consumption is, P = (+P) + (-P) Unlike the condition in the purely reactive circuit, however, in the combined RX circuit the area under the +P curve is always larger than that enclosed by the -P curve. Thus the integrating device, (wattmeter), the deflection of which indicates the difference in these areas, will always indicate some + power. The greater the R/X ratio of the load circuit constants, the greater will be the ratio of true power/apparent power and the greater the power factor. It should be noted that this ratio used in power circuits is simply the inverse of the KVA/KW peak amplitude of the curves. In gaining a true conception of power, it is important that the area relation be understood. Earlier in this assignment power is defined as the "time rate at which work is done". At any instant during a cycle the

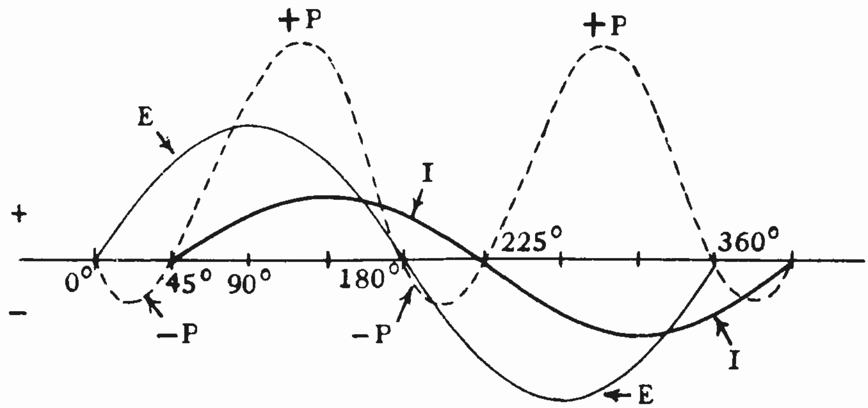


Fig. 7.—**Power waveform for a resistive and reactive circuit.**

ratio used in tuned circuit calculations and explained in Assignment 21.

Under any conditions the -P area can never exceed the +P area because it is impossible to take more power from a reactance than has been delivered to it. In fact, since it is impossible to construct a truly zero loss device, the positive area will always exceed the negative area.

In discussing the power curves of Figures 5, 6 and 7 the term "area" is emphasized in speaking of the +P and -P curves and not the actual rate at which work is being done is the product of $e_{inst} \cdot i_{inst}$ and is represented by some amplitude on the power curve for that particular instant. By taking the R.M.S. (root mean square) value of all the instantaneous values the effective value as indicated by the wattmeter is determined. But, where the circuit contains a reactive component, the mean square from which the root is derived is the mean of the resultant of the squares of the +P values minus the squares of the -P values.

The true power can be obtained

mathematically by integration of the equation from which the power curve is drawn; or by drawing the power curve to scale, measuring a large number of uniformly separated points over the cycle, and then determining the root mean square of all the points. The most simple method, where an actual power circuit is involved, is to use a wattmeter which performs the integration by electromechanical means. The wattmeter can be used only within the power frequency range. Mathematical means or I^2R measurements must be employed at the radio frequencies.

Consider a practical example of an A.C. circuit, to find the power expended and the power factor. Voltage 516 volts, Frequency 60 cycles, Inductance .2 henry, Capacity 30 microfarads, Resistance 50 ohms. See Figure 8.

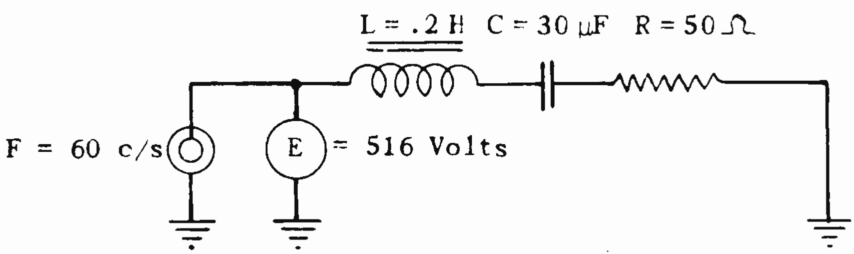


Fig. 8.—An a-c circuit from which the power expended can be calculated by two methods.

$$X_L = 2\pi FL = 6.28 \times 60 \times .2 = 75.4 \text{ ohms}$$

$$X_c = \frac{1}{2\pi FC} = \frac{1}{628 \times 6 \times 3 \times 10^{-6}} = 88.4 \text{ ohms}$$

$$Z = \sqrt{R^2 + (X_c - X_L)^2} = \sqrt{50^2 + (88.4 - 75.4)^2} = \sqrt{50^2 + 13^2}$$

$Z = 51.6$ ohms. $X = X_c - X_L = 88.4 - 75.4 = 13$ ohms.

$$\text{Tan } \theta = X/R = 13/50 = .26 = 15^\circ \text{ lead}$$
$$\text{Cos } 15^\circ = .966$$

$$PF = \text{Cos } \theta \cdot 100 = .966 \times 100 = 96.6^\circ$$

$$I = E/Z = 516/51.6 = 10 \text{ amperes.}$$

$$P = EI \text{ Cos } \theta = 516 \times 10 \times .966 = 4984{,}5 \text{ watts.}$$

Also

$$P = I^2R = 10 \times 50 = 5000 \text{ watts.}$$

The discrepancy between the power calculations by the two methods is due to decimals being dropped here and there throughout the calculation and by the use of the nearest angle in degrees instead of the exact angle. The discrepancy in the two methods is only 15.5 watts in 5000, a negligible error of .3 per cent which easily can be reduced by accurate calculations.

The power factor and angle of current lead or lag may also be determined by the use of an ammeter, voltmeter and wattmeter as explained above. The power factor is defined as the true power indicated by a wattmeter, divided by the apparent power which is the product of simultaneous readings of the ammeter and voltmeter.

For example: Assume ammeter reading of 40 amperes, voltmeter reading of 220 volts and wattmeter reading of 6400 watts.

$$\text{Apparent Power} = EI = 220 \times 40 = 8800 \text{ watts}$$

True Power = 6400 watts (indicated by wattmeter)

$$\text{Power Factor (Decimal)} = \frac{\text{True Power}}{\text{Apparent Power}} = \frac{6400}{8800} = .727$$

$$\text{Power Factor (Per cent)} = .727 \times 100 = 72.7 \text{ per cent.}$$

The power factor is also equal to the Cosine of the angle of lead or lag, therefore,

$$\cos \theta = \text{PF (Decimal)} = .727$$

From a table of trigonometric functions, $\cos^{-1} .727 = 43°$. Whether the angle is one of lead or lag must be determined from the type of apparatus in the circuit. If the load is preponderantly inductive the current will lag; if preponderantly capacitive the current will lead E.

Usually in a complex circuit the resistance is distributed through several circuit components rather than being lumped at one point. If the circuit is operating at radio frequency, power dissipation must be calculated on the basis of I^2R. Consider the LCR network shown in Figure 9(a) and the equivalent circuit in Figure 9(b). In the equivalent circuit the resistance R_1, R_2 and R_3 which actually, as shown in 9(a), are distributed throughout their respective inductance coils, are shown as separate components. These values of R.F. resistance can be determined by measurement of each coil at the frequency to be used and must not be taken as the d.c. values. In practice this might be the coupling circuit between a transmitter vacuum tube power amplifier and an antenna with C_3 and R_4 forming respectively the capacity and resistance of the antenna. Except at very high frequencies the losses in the capacitors may be neglected.

R.F. ammeters I_1, I_2 and I_3 in-

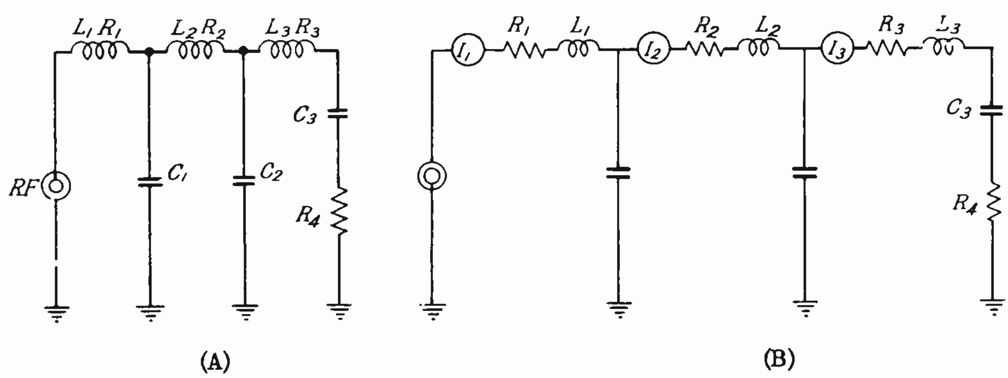


Fig. 9.—An LCR network and its equivalent circuit the resistance being distributed in each coil.

dicate that the current will be different in different parts of the complex circuit. Therefore it will be most simple to calculate separately the power dissipation of the individual resistance components in order to determine the total power expended.

The total power dissipation is the SUM of the power dissipation in all the individual resistances.

$$P = I_1{}^2R_1 + I_2{}^2R_2 + I_3{}^2R_3 + I_3{}^2R_4$$

Since R_3 and R_4 are in series, the same current, I_3, flows through both and this current is used in calculating the power dissipation in both resistances.

Assume numerical values of current and resistance which might be measured in the circuit of Figure 9 if it were used in a 5 KW radio transmitter power output and antenna circuit. The measured values are:

I_1 = 1.5 amperes	R_1 = 6 ohms
I_2 = 30 amperes	R_2 = .3 ohms
I_3 = 15 amperes	R_3 = .4 ohms
	R_4 = 22 ohms

Substituting these numerical values in the power equation for the circuit.

$$P = (1.5^2 \times 6) + (30^2 \times .3) + (15^2 \times .4) + (15^2 \times 22)$$

$$P = 13.5 + 270 + 90 + 4950$$

$$P = 5323.5 \text{ watts.}$$

From this it would be determined that to get 4950 watts from the circuit input to the actual antenna resistance, in this case 373.5 watts must be dissipated in the necessary coupling circuits. Very often it would not be necessary to break down the total power dissipation into the individual losses. Such an analysis does show, however, how rapidly the non-useful losses can add up with even small values of R.F. resistance and it emphasizes the necessity for designing the coils in high current R.F. circuits to have minimum R.F. resistance. Note that in the case of L_1, the relatively high resistance of 6 ohms is not important because the current is small. On the other hand, in the .3 ohm resistance of L_2 the power dissipation is quite large (270 watts) because the large current (30 amperes). Therefore in designing R.F. circuit components, it is first necessary to know the conditions under which they will operate.

POWER OUTPUT OF VACUUM TUBES.— When working with high power water cooled tube transmitters at high frequency it is very necessary to know just how efficiently the transmitter is operating, much more so than in the case of low power transmitters. It has been stated that the I^2R method of determining the R.F. circuit power at very high frequencies is not always accurate due to the variations of voltage and current distribution in the very high frequency circuits making it difficult to determine just what the resistance of the circuit actually is. Many of the measurements that can be made at low and intermediate radio frequencies prove inaccurate when made at 10 or 15 megacycles or higher. Nevertheless, it is of extreme importance, when adjusting a high power transmitter, to know whether the power is getting to the output circuit or being expended in heating the tube plate.

In a vacuum tube, (high power

transmitting), a high percentage of the power expended within the tube is in heating the plate by electronic bombardment. The radiation of this heat raises the temperature of the cooling water that circulates around the plate. The heat produced varies as the square of the current, or directly as the power expended. Therefore in order to raise the temperature of the water in the cooling system one degree, a specific amount of power must be expended. This value of course is a function of the plate area, the geometry of the water system and the rate of flow of the water through the system. If the amount of power that, under the specified conditions, will raise the temperature of the water one degree, is known, it is a simple matter to compute the power expended in the tube when the temperature of the water in the cooling system is raised any measured amount.

If such measurement indicates that 3000 watts is expended in the tube, and the readings of the d.c. plate ammeter and voltmeter indicate that the power delivered to the tube and circuit is 6000 watts, then the difference between 6000 and 3000 watts or 3000 watts must be consumed in some parts of the circuit other than the tube itself. In this case the tube is delivering 3000 watts to the output circuit and the antenna system, and the power conversion efficiency of the tube is 50 per cent. A given power dissipation in the form of heat will raise the temperature of a continuous flow of water by some definite amount, depending upon the rate of flow of the water and the radiating surface over which the flow of water passes. If the same water is continually recirculated and passed through a cooling system, the temperature of the water at the input and output of the tube water jacket must be just as carefully noted because it is the *temperature rise* in passing through the water jacket that is important.

In making this measurement the temperature increase caused by heat radiation from the filament must be considered. The effect of filament heating is measured with the plate voltage removed; the temperature rise in degrees is noted and subtracted from the measured temperature increase with the tube in normal operation. This may be a quite large factor when the tube is operating at high plate efficiency.

If one kilowatt dissipated at the plate will raise the water temperature at the output 5 degrees above that at the input, then two kilowatts will cause a 10 degree temperature rise, etc. Two thermometers are required, one sealed into the input water supply, the other into the output of the water jacket. By applying a d.c. voltage to the plate with variable grid bias to adjust the plate current, a calibration is made to determine the power expenditure necessary for each degree of temperature rise.

In making the calibration measurement, the water rate of flow is noted and held constant, and the power input is held constant until no further increase of temperature, as indicated by the difference between the readings of the two thermometers, is observed. When the temperature difference ceases to rise, a notation is made of the temperature of the input water and of the outlet water from the water jacket. The difference in degrees between these temperatures is the amount of rise caused by the power dissipation in the tube. The temperature rise in degrees divided into the known power in watts gives the power necessary to raise the temperature one degree. Assume that plate power dissipation of 2500 watts raises the temperature 12° Centigrade. Then the power required for each degree centigrade of temperature increases is 2500/12 or 208 watts.

When using the calibration similar procedure is followed. The transmitter is adjusted to normal operation at the desired frequency. Then the key is locked and the transmitter is operated until the difference between the input and output temperatures is constant. *(It is important that the rate of flow of the water be the same as when the calibration was made.)* At this point the outlet and input temperatures are noted. Assume that the input temperature is 34°C and the outlet temperature 48°C. The plate voltage and the plate current also are noted. Assume that $E_p = 12000$ volts and $I_p = .48$ amperes.

The temperature increase is 48° - 34° or 14°. According to the calibration the power expended in the tube is 208 watts per degree. The power dissipated at the plate is 208 × 14 = 2912 watts.

The power input to the tube is $E_p I_p = 12000 \times .48 = 5760$ watts. Of the total power input, 2912 watts are dissipated in the tube itself. The power transferred to the output circuit is 5760 - 2912 = 2848 watts.

The plate efficiency expressed as a decimal equals OUTPUT/INPUT: the efficiency in this case is 2848/5760 = .494 = 49.4 per cent.

It must be remembered that all of the power delivered by the tube is not transferred to the antenna. A certain amount of power is expended in heat in the output tank circuit of the tube. This is shown for the circuit of Figure 9. At the low and intermediate frequencies most of the circuit I^2R loss is in the inductance, only a comparatively small percentage occurring in the capacitors, shields, etc. This condition still exists at frequencies as high as 4000 to 5000 kilocycles. As the frequency is further increased, however, a greater and greater percentage of the circuit losses occur in the capacitors, shields, etc., and a smaller percentage in the inductance. At frequencies in the order of 15 MC/s and higher the losses in the inductance form the smaller proportion of the circuit losses. At these frequencies the proportion of capacity and stray losses will be increased by decreasing the circuit capacity and correspondingly increasing the inductance, due to the higher voltages developed in the circuit across the capacitor dielectric, insulators, etc. Thus at very high frequencies the circuit loss conditions are often the reverse of the conditions at the lower frequencies, and this must be taken into consideration in the design of the circuit.

In computing the operating efficiency of a transmitting vacuum tube, the power input usually is taken as the input to the plate circuit only, neglecting the power expended in heating the filament.

CIRCUIT LOSSES.—Expenditure of power in a circuit represents the conversion of the basic electrical energy to some other form of energy. In the simple example of a soldering iron, the electrical energy is converted into heat, the heat being made to do useful work in melting the solder and raising the temperature of the metals being joined.

In the somewhat more complex case of a motor-generator: Assume that a d.c. motor is driving an alternator which in turn is feeding a rectifier which supplies high voltage direct current to a radio transmitter. Assume that the d.c. motor power line meters indicate a load of 40 amperes at 220 volts. From Ohms law it would seem that the d.c. load circuit should have a resistance of E/I, 220/40 = 5.5 ohms. The power expended in the circuit is then EI or I^2R, 220 × 40 or 40^2 × 5.5, in either case 8800 watts. From meter indications in the d.c. input circuit it cannot be determined whether the power of 8800 watts is expended in heating a simple resistance or in operating a motor; but if the power circuit is opened and the d.c. resistance of the motor is measured between terminals, the resistance will be found to be much less than 5.5 ohms.

In tracing all the power losses in the motor and associated circuits, however, it will be found that all of the electrical energy actually is converted into heat or radiated energy at some point along the circuit. Current flows through the motor armature and field windings; the power loss here is the sum of I^2R in each winding, R being the actual ohmic resistance of the winding. Thus, if the motor is shunt wound with field resistance of 110 ohms and armature resistance of .1 ohm, the field current will be 220/110 = 2 amperes and the power dissipated in the field winding will be 2^2 × 110 = 440 watts. Since the total motor current is 40 amperes, the armature current must be 40 - 2 or 38 amperes and the direct armature resistance power loss will be 38^2 × .1 = 144 watts. After the motor has been running awhile, inspection will show that the bearings heat somewhat so that some power is expended in friction. In the alternator similar power expenditures occur in the field and armature windings and in friction.

The output of the alternator is divided. One branch of the power circuit is used to heat the filaments of the transmitting tubes, the power expenditure occurring in the filaments themselves and in the filament transformer windings. The other branch circuit connects to the high voltage rectifier. Power in the rectifier is expended in heating the filaments of the rectifier tubes, at the anodes of the rectifier tubes, and in the transformers and filters.

The output of the high voltage rectifier connects to the transmitter plate circuits where power is expended in heat at the tube plates and in the tank circuits. Finally the radio frequency power output of the transmitter is delivered to the antenna where it is manifest in the form of I^2R loss and radiation of energy from the antenna. Even in the antenna non-useful losses are present; only a certain proportion of the total antenna power is actually radiated, the remainder being expended in heat in the antenna wire, the ground system and in the dielectric of the insulators and the suspension system. The proportion of the antenna power actually radiated is a function of the antenna dimensions, shape, operating frequency, ground system, and to some extent its location.

From the above discussion it will be apparent that the radio frequency power finally reaching the antenna is only a small percentage of the power actually taken from the original power source. In the case of one shipboard radio telegraph transmitter having rated antenna output of 100 watts, the manufacturer's specifications state that a minimum of 1.8 KW will be taken from the power source when the key is closed. In other words, only 5.5 per cent of the original input power to the motor-generator is actually delivered to the antenna, and even this is not all useful power due to the non-useful losses in the antenna itself. Similar percentage figures for several transmitters are given earlier in this lesson.

In the case of a broadcast transmitter the ratio of antenna to input power may be greater or less than the above, depending upon the circuit and the arrangement of tubes, the type of power equipment used, and the rated power output of the transmitter. Where the transmitter is designed to operate directly from the commercial A.C. power supply without the use of motor generators, somewhat greater overall efficiency should be expected—everything else being equal—due to the fact that the motor generator losses are eliminated. Also, a high power transmitter should have a somewhat greater overall efficiency than a low power transmitter employing a similar circuit due to the better ratio of plate to filament power in the higher power tubes. This is counteracted to some extent, however, by the fact that low power tubes with their associated circuits must be used to excite the high power stage. In a number of modern broadcast transmitters the arrangement is somewhat as follows: a 100-250 watt transmitter excites a 1 KW amplifier which in turn excites a 5 KW amplifier which in turn excites a 50 KW amplifier.

As an example of the increased power efficiency obtained at very high power, the results obtained in one 500 KW broadcast transmitter will be interesting. This transmitter consists of a 500 KW Class C radio frequency amplifier excited by a 50 KW transmitter and modulated by a 350 KW Class B audio amplifier. With normal power output the power input to the 500 KW amplifier is 1150 KW for zero modulation, 1600 KW for 100 per cent sinusoidal modulation. This includes the power to all auxiliary apparatus but not to the 50 KW exciter. The power input to the entire transmitter with all auxiliary apparatus under normal operation is approximately 2000 KW. Compared with the output of 500 KW, this indicates an overall efficiency of about 25 per cent, quite high as compared with the 5.5 per cent for the low power telegraph transmitter. Of course, high overall efficiency is of much greater importance in the case of high power transmitters than with low power transmitters because of the greater cost of power and of circuit components in the high power transmitter.

The importance of proper circuit selection as a consideration in obtaining high overall efficiency also is demonstrated in the 500 KW transmitter installation. By operating the final amplifier Class C and modulating this amplifier direct by a Class B audio amplifier, rather than modulating at low level and then operating the final stage as a linear amplifier, an annual saving of approximately $25,000 was effected. Circuits are now available which permit even greater overall efficiency and reduction in operating cost.

R.F. LOSSES.—Radio frequency power loss occurs in every component part of the circuits carrying radio frequency current. To the R.F. circuit losses must be added the losses in adjacent metallic bodies in which eddy currents may be induced and in non-conducting bodies which may be included in an electro-static field. As an example of the former, the eddy currents induced in a metallic shield placed around a receiver R.F. coil result in I^2R losses in the shield, these losses being reflected as increased coil resistance which decreases the Q, (X_L/R), of the coil; this reflected resistance may be sufficiently large to materially affect the operation of the circuit.

An example of R.F. power loss in non-conductors is the dielectric loss in the insulator which supports the extreme end of an antenna, the very high voltage occuring at this point often making such power loss quite appreciable. This power expenditure is reflected in increased antenna resistance. Since the power in the antenna is calculated on the basis of I^2R, it will be seen that such losses simply dissipate power from the transmitter but do not add to the amount of energy radiated.

In the ordinary well designed radio frequency circuit the greater proportion of the non-useful losses are in the inductance coil and may be of considerable magnitude due to high frequency skin effect. This effect produces some peculiar conditions at radio frequencies. For example, in a particular coil design problem for a broadcast receiver, two coils were wound having the same diameter and the same number of turns, one being wound with No. 20 copper wire, the other with No. 28 copper wire. The d.c. resistance of No. 28 wire is approximately 6.5 times greater than that of No. 20 wire. When the R.F. resistance of the two coils was measured at 1000 KC/s, it was found that the resistance of the coil of No. 28 wire was only approximately twice as great as that wound with No. 20 wire.

Therefore, the added resistance due to the use of a smaller wire size at radio frequency is not nearly so great as would be the case in a d.c. circuit. At radio frequencies the current flows almost entirely near the surface of the conductor, the depth of penetration being an inverse function of frequency. In the case of very small wire, the given current depth more nearly approaches the center of the wire and more of the total copper is usefully employed in carrying current, making the difference between the d.c. and R.F. conditions less than in the case of a conductor of greater diameter. In a large conductor there is additional loss due to eddy currents in the center of the wire caused by induction from the current flowing near the surface. This is one reason why the R.F. resistance of copper tubing is less than that of a solid conductor having the same outside diameter. In addition to the reduction of eddy current loss, advantage is taken of the added surface of the inside of the tube, the total surface area in thin wall tubing being almost double that of a solid conductor.

For the same reason the radio frequency resistance of stranded wire is less than that of a solid wire having the same cross-sectional area because the total surface area of the stranded wire is greater and there is less total copper that is not usefully employed in carrying current. Where the individual strands are very small and each is separately insulated, as in Litz cable, the resistance for a given amount of copper is still further reduced.

In high quality receiver coils, particularly in the intermediate frequency transformers of superheterodyne receivers, Litz wire is extensively employed. This results in a coil of higher Q, permits the circuit loss to be kept to a minimum, increases the circuit selectivity, and permits greater amplifier gain per stage. It is found, however, that at very high radio frequencies, in order of several megacycles, the advantages of Litz wire are lost due to the increased dielectric losses in the insulation between strands. At the broadcast and intermediate frequencies, Litz wire allows a considerable reduction in coil resistance. Combined with the advantage of iron core construction, it becomes possible to design coils having much higher Q than is practical by the use of solid wire on an air core.

In high power transmitters where it is practical to wind the coils with large thin wall copper tubing, the R.F. resistance of tank circuits can be made very small. In one high power broadcast transmitter the Q of the final stage tank coils is 1200. In receiver coils Q of 150 is quite high. In view of the fact that tank circuit loss in transmitters represents wasted power, the advantage of low R.F. coil resistance will be seen. (It should be mentioned at this point, however, that where it is necessary to amplify a modulated carrier and the power must be dissipated in the tank circuit itself, as in the case of the intermediate linear amplifier of a broadcast transmitter, a high Q circuit sometimes cannot be used due to the excessive selectivity which would destroy the fidelity of reproduction. However, in the final amplifier stage which is coupled to the antenna, the high Q coil may be used and the desired resistance reflected into the tank circuit from the antenna load by proper coupling).

Dielectric loss in capacitors becomes increasingly important at the very high frequencies, that is, frequencies in the order of 10 MC/s and higher. A type of capacitor which performs quite satisfactorily at broadcast frequencies may, when operated at the much higher frequencies, add sufficient dielectric loss to the circuit to make the operation entirely unsatisfactory. Such a capacitor, if used in a transmitter, may overheat and break down. In a receiver a capacitor of poor design may introduce sufficient high frequency loss to broaden the tuning and make the R.F. amplifier gain negligible.

In a high voltage circuit, particularly in the case of a transmitting antenna operated at a quite low frequency, corona loss may become very high. In fact, it is possible for corona loss to reach such proportions that further increase in the power input—with a consequent increase in antenna voltage—may actually decrease the energy radiated. This is discussed in greater detail in later assignments.

It is essential that the radio engineer clearly understands the relation between the useful and non-useful power expenditures in a circuit. A principal object in the adjustment of a transmitter is to obtain the correct relation between those two losses. It is very possible, as will be explained in the study of vacuum tube circuits, to obtain very high operating efficiency at the expense of greatly reduced power output, or to get large output at quite low operating efficiency. Either adjustment usually would be incorrect, the former decreasing the effectiveness of the transmitter, the latter probably resulting in an overload and possible damage to some part of the equipment, or in the use of an unnecessarily large tube complement. In every case there is some optimum set of adjustments which will permit rated power output with good operating efficiency *under the conditions for which the circuit was designed.*

In the design of a transmitter there is some combination of tube type, operating voltages and currents, and circuit constants that will give the best all-around results *under the conditions for which the transmitter is to be used.* This latter statement is important. Good design of a 10 KW radio telegraph transmitter—tubes, circuit constants, and voltages—*would be entirely unsuitable* for a 10 KW broadcast transmitter, and vice-versa. This point must be carefully remembered in the subsequent study of tubes and circuits, and in all practical work with equipment, because the operating conditions of a tube and circuit for modulated and unmodulated radio frequency operation are entirely dissimilar. Design or adjustment should not be attempted until those differences are *thoroughly understood.*

V 9174-33

POWER CONSUMPTION IN ELECTRICAL CIRCUITS

EXAMINATION

1. Explain what is meant by the "Power expended in a circuit"? How is this power expended? *Explain fully.*

2. (A) Explain in detail how you would measure the radio frequency resistance of an antenna.

   (B) Explain the precautions necessary in order to obtain an accurate measurement.

3. (A) Explain in detail the advantage of knowing the power expended in the antenna system. Efficiency can be computed!

   (B) Is all the power in the antenna expended usefully? *Explain.*

4. (A) Explain fully how the efficiency of a transmitter is computed.

   (B) What is the difference between the overall efficiency and the tube plate circuit efficiency? *Explain.*

5. A series circuit is composed of a 500-cycle alternator, a 15 microfarad condenser, a .025 henry inductance and a resistance of 20 ohms. The effective alternator voltage is 440 volts. Find the Power Factor of the circuit and the power expended. *PROVE your answer.*

6. Television Transmitter No. 1 delivers 14.14 amperes into an antenna the resistance of which is 50 ohms at the input terminals. Television Transmitter No. 2 delivers 10 amperes into an antenna having a resistance of 70 ohms. The total power input to each is 25 kw. Find the efficiency of each transmitter and state which is the more efficient. *Show all work.*

7. A television transmitter delivers 8.33 amperes into a 72-ohm antenna. If the power is decreased until the antenna ammeter indicates only 4.17 amperes how much has the power been decreased? *Show all figures and explain.*

8. A series circuit consists of L, C, and R. X_L = 145 ohms, X_c = 216 ohms, R = 125 ohms. The voltage drop across the resistance is 460 volts.

   (A) What is the voltage drop across L, across C, across the terminals of the alternator?

   (B) Show all voltages on a vector diagram.

9. (A) In what part of the tube load circuit is most of the power dissipated?

   (B) Explain types of design that can be used to minimize the circuit losses.

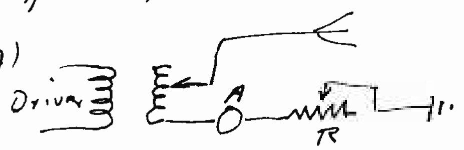
   (C) Explain the reason for the effectiveness of each.

10. The cooling water temperature at the inlet of the water jacket of an 891 power amplifier tube is 40° C when the rate of water flow is adjusted to 2 gallons per minute. With only the filament voltage applied the temperature at the water jacket outlet is found to settle at 42° C. When d.c. plate voltage of 2,000 volts is applied without excitation the temperature of the water rises to 50° C at a plate current of .8 ampere. What will be the power delivered to the load when the stage is adjusted for normal operation with a plate voltage of 8,000 volts, an average plate current of 1,000 ma and the outlet water temperature is found to stabilize at 57° C?

V 9174-33

1. Power is the time rate at which work is done. It is expendended in a circuit only in overcoming resistance of the circuit, and is usually expendend in the form of heat, due to collisions of electrons in the conductors or to the rapid displacements of electrons in dielectrics of capacitors.

2. (A)



A - Ammeter
R - calibrated Resistance

Note ammeter reading with all of the calibrated resistance out of the circuit. Then insert resistance in circuit until ammeter reading is reduced by one half. As current varies inversely with resistance, the resistance has been doubled when the current has been halved. Therefore the resistance added is equal to the antenna resistance.

(B) In order to obtain an accurate measurement the applied voltage to the circuit must be held absolutely constant.

3 A. Current reading alone is no indication of power. Power = I^2R, so with two antennas drawing equal currents, more power is expended in the one having higher resistance. [illegible]

True, but doesn't answer question

B. No. Some is expended non usefully as heat due to coil resistance, ~~etc.~~ resistance of antenna wire, ground system, etc.

4.(A) Efficiency of any apparatus is the ratio of power in to power out. Power in can be observed by means of a wattmeter in the power line to the transmitter. Power out is the power actually delivered to the ~~Antenna~~ plate tank circuit. ~~Antenna~~ ~~resistance may be found~~ In overall eff., Po is power radiated by antenna.

Eff. = $\frac{Po}{Pin}$

How is Pa determined

B. The tube plate circuit efficiency is the inverse ~~ratio~~ ratio of the power input to the tube ($E_p I_p$) to the power out to the tank circuit, which is the power in minus the power dissipated at the plate of the tube. The overall efficiency would be much lower as power expended in the filaments and all other circuit components would be included.

5. $X_L = 2\pi FL = 6.28 \times 500 \times .025 = 78.5\ \Omega$

$X_c = \frac{1}{2\pi FC} = \frac{1}{6.28 \times 500 \times 15 \times 10^{-6}} = 21.2\ \Omega$

$X = 57.3$

$\tan\theta = \frac{X}{R} = \frac{57.3}{20} = 2.865$

$\theta = 70°46'$ $\cos\theta = PF = .33$

$Z = \sqrt{20^2 + 57.3^2} = \sqrt{3684} = 60.7\ \Omega$

$I = \frac{E}{Z} = \frac{440}{60.7} = 7.25$ amp.

Power $= I^2R = 7.25^2 \times 20 = 1052$ watts

$P = EI\cos\theta = 440 \times 7.25 \times .33 = 1052$ watts

V 9174-33

6. Power out #1 = $14.14^2 \times 50$ = 10 KW ✓

Power out #2 = $10^2 \times 70$ = 7 KW. ✓

Eff. #1 = $\frac{10}{25} \times 100$ = 40 % ✓

Eff. #2 = $\frac{7}{25} \times 100$ = 28 % ✓

~~#2 is more efficient~~ ✗

#1 is 40% eff., so #1 is more efficient!

7. Power = Current squared × Resistance

R remains constant so —

$P = I^2R = 8.33^2 \times 72$ = 5 KW ✓

decreased $P = I^2R = 4.17^2 \times 72$ = ~~1.33~~ 1.252 KW

Power has been decreased 5 - ~~1.33~~ 1.252 = ~~3.67~~ 3.748 KW

~~Should~~ explain! See solution

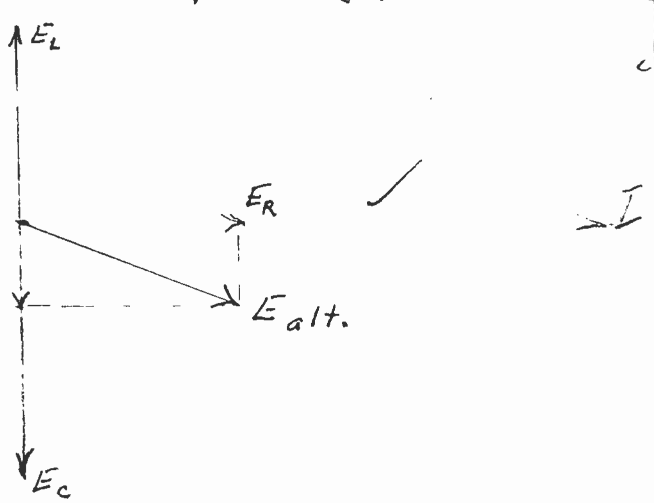
8. $I_R = \frac{E_R}{R} = \frac{460}{125}$ = 3.68 amps. ✓

$E_L = X_L I$ = 145 × 3.68 = 534 Volts

$E_c = X_c I$ = 218 × 3.68 = 795 volts

$E_{alt} = \sqrt{460^2 + (795-534)^2}$ = 506 ✗ volts

check math! See solution, also



9. (The largest single source of power dissipation in the circuit is at the tube plate due to electron bombardment of the plate). Coils are the next highest.

Plate of tube is not considered as being the load!

Any design that lowers the RF resistance lowers the circuit losses. As most of the loss occurs in the coil, the coil design is very important. Increasing the surface area by using stranded wire decreases the RF resistance as RF current flows only on and near the surface of the conductor. Litz wire is very good for receiver coils except at very high frequencies where the dielectric losses of the insulation predominate.

In high power transmitters coils are made of tubing. This gives large surface area for total amount of copper and eliminates eddy current losses at the center of the conductor.

10. $T_2 - T_1 = 50 - 42 = 8°$

P to raise T 8° = 2000 x .8 = 1600 watts

P per degree = 1600/8 = 200 watts.

P in = 8000 x 1 = 8000 watts

P dissipated in plate = 200 x (57 - 42 = 3000 watts

Power delivered = 8000 - 3000 = 5000 watts

or 5 KW.

POWER CONSUMPTION SOLUTIONS

6. Television Transmitter No. 1 delivers 14.14 amperes into an antenna the resistance of which is 50 ohms at the input terminals. Television Transmitter No. 2 delivers 10 amperes into an antenna having a resistance of 70 ohms. The total power input to each is 25 KW. Find the efficiency of each transmitter and state which is the more efficient. Show all work.

No. 1 $P = I^2R = 14.14 \times 14.14 \times 50 = 10{,}000$ watts or 10 KW.
No. 2 $P = I^2R = 10 \times 10 \times 70 = 7{,}000$ watts or 7 KW.
Efficiency = $(Po/Pi) \times 100 = (10/25)100 = 40$ percent for Ant. No. 1
Efficiency = $(7/25)100 = 28$ percent for Ant. No. 2
Antenna No. 1 is more efficient as shown by the figures.

7. A television transmitter delivers 8.33 amperes into a 72-ohm antenna. If the power is decreased until the antenna ammeter indicates only 4.17 amperes, how much has the power been decreased? Show all figures and explain.

Condition one, $P = 8.33 \times 8.33 \times 72 = 5{,}000$ watts
Condition two, $P = 4.17 \times 4.17 \times 72 = 1{,}250$ watts
Decrease in power is $5{,}000 - 1{,}250 = 3{,}750$ watts

Since R is constant, the power dissipation varies as I^2. If the current is reduced 1/2, then the power is reduced to 1/4 of its original value.

8. A SERIES CIRCUIT CONSISTS OF L, C, AND R. X_L EQUALS 145 OHMS, $X_C = 216$ OHMS, AND R = 125 OHMS. THE VOLTAGE DROP ACROSS THE RESISTANCE IS 460 VOLTS. WHAT IS THE VOLTAGE DROP ACROSS L, ACROSS C, AND ACROSS THE TERMINALS OF THE ALTERNATOR? SHOW ALL VOLTAGES ON A VECTOR DIAGRAM.

$$Z = \sqrt{R^2 + X^2} = \sqrt{125^2 + 71^2} = \sqrt{15625 + 5041}$$

$$Z = \sqrt{20666} = 143.8$$

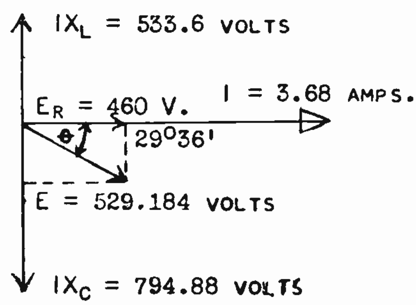
$$I = E/Z = \frac{460}{125} = 3.68 \text{ AMPS.}$$

$$IX_L = 145 \times 3.68 = 533.6 \text{ VOLTS}$$

$$IX_C = 216 \times 3.68 = 794.88 \text{ VOLTS}$$

ALTERNATOR $E = E = IZ = 3.68 \times 143.8 =$
$= 529.184$ VOLTS

$$\text{TAN } \theta = \frac{X}{R} = \frac{216 - 145}{125} = \frac{71}{125} = 0.568.$$



$\theta = 29°36'$ LEAD.

9. IN WHAT PART OF THE TUBE LOAD CIRCUIT IS MOST OF THE POWER DISSIPATED? EXPLAIN THE TYPES OF DESIGN THAT CAN BE USED TO MINIMIZE THE CIRCUIT LOSSES. EXPLAIN THE REASON FOR THE EFFECTIVENESS OF EACH.

MAJOR PART OF POWER IS DISSIPATED IN INDUCTANCE COIL. IN BROADCAST RECEIVER COULD USE LITZ WIRE OR SMALLER SIZE WIRE--IN RF CIRCUITS CURRENT TRAVELS ON OUTSIDE SURFACE OF WIRE DUE TO SKIN EFFECT AND THEREFORE TUBING IS USED HERE. LITZ WIRE IS USED IN IF TRANSFORMER, RESULTS IN HIGHER Q, GREATER AMPLIFIER GAIN PER STAGE LESS CIRCUIT LOSS. IN HIGH POWER TRANSMITTERS COPPER TUBING USED DUE TO EDDY CURRENT LOSSES, THE RESISTANCE INCREASES WITH SOLID CONDUCTOR.

10. THE COOLING WATER TEMPERATURE AT THE INLET OF THE WATER JACKET OF AN 891 POWER AMPLIFIER TUBE IS 40° C WHEN THE RATE OF WATER FLOW IS ADJUSTED TO 2 GALLONS PER MINUTE. WITH ONLY THE FILAMENT VOLTAGE APPLIED THE TEMPERATURE AT THE WATER JACKET OUTLET IS FOUND TO SETTLE AT 42° C. WHEN D-C. PLATE VOLTAGE OF 2000 VOLTS IS APPLIED WITHOUT EXCITATION, THE TEMPERATURE OF THE WATER RISES TO 50° C AT A PLATE CURRENT OF .8 AMPERE. WHAT WILL BE THE POWER DELIVERED TO THE LOAD WHEN THE STAGE IS ADJUSTED FOR NORMAL OPERATION WITH A PLATE VOLTAGE OF 8000 VOLTS, AN AVERAGE PLATE CURRENT OF 1000 MA AND THE OUTLET WATER TEMPERATURE IS FOUND TO STABILIZE AT 57° C?

8° C DIFFERENCE

$P = EI = 2000 \times .8 = 1600$ WATTS

$P \text{ (expended per } 1^\circ) = \frac{1600}{8} = 200$ watts

$57 - 40 = 17^\circ$ change less 2° difference $= 15^\circ$ total change

$8000 \times 1 = 8000$ watts input

$15 \times 200 = 3000$ watts dissipated at the plate

$8000 - 3000 = 5000$ watts delivered to the load at

an efficiency $= (5/8) \times 100 = 62.5$ percent

5. A SERIES CIRCUIT IS COMPOSED OF A 500 CYCLE ALTERNATOR, 15 MICROFARAD CONDENSER, A .025 HENRY INDUCTANCE AND A RESISTANCE OF 20 OHMS. THE EFFECTIVE ALTERNATOR VOLTAGE IS 440 VOLTS. FIND THE POWER FACTOR OF THE CIRCUIT AND THE POWER EXPENDED. PROVE YOUR ANSWER.

$$X_C = \frac{1}{2\pi FC} = \frac{1}{6.28 \times 500 \times 15 \times 10^{-6}} = \frac{10^4}{471} = 21.2 \text{ OHMS}$$

$$X_L = 2\pi FL = 6.28 \times 500 \times .025 = 78.5 \text{ OHMS}$$

$$X = X_L - X_C = 78.5 - 21.2 = 57.3 \text{ OHMS INDUCTIVE}$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{20^2 + 57.3^2} = \sqrt{400 + 3283.29} = \sqrt{3683.29} = 60.7\,\Omega$$

$$\text{TAN } \theta = \frac{X}{R} = \frac{57.3}{20} = 2.87 \qquad \theta = 70^\circ 48' \text{ LAG}$$

$$\text{POWER FACTOR} = \cos\theta = .33 = 33 \text{ PER CENT}$$

$$I = \frac{E}{Z} = \frac{440}{60.7} = 7.25 \text{ AMPERES}$$

$$\text{POWER} = I^2R = 7.25^2 \times 20 = 1051 \text{ WATTS}$$

<u>PROOF:</u> APPARENT POWER = $EI = 440 \times 7.25 = 3190$ WATTS

<u>POWER FACTOR</u> $= \frac{\text{REAL POWER}}{\text{APPARENT POWER}} = \frac{1051}{3190} = .33 = 33$ PERCENT, CHECK

<u>POWER</u> = APPARENT POWER x POWER FACTOR = $3190 \times .33 = 1053$ WATTS. CHECK.