Fundamental Electric Power Calculations

By P. A. ALTENDORF
Texas Electric Service Co.
Midland, Texas

It would seem that before we can get into formulas and actual power calculations, it would be worth while to review a definition of electricity and study some of the instruments used to determine the quantities that are needed in power calculations.

Until quite recently no one knew for sure just what electricity was. But as a result of advanced research, it has been determined that electricity is the substance of which everything is composed. The electron theory states that all matter, everything we can feel, see, taste or smell, when finally broken down, consists of little charges of electricity. If we are to define electricity, then we need to know what the electron theory is and study the composition of matter.

Scientists have shown that all matter is made up of little particles called molecules. If we should take a grain of salt and break it down into the smallest part that would still have all the properties of salt, then the little part would be a molecule of salt. Molecules are so small that they cannot be seen even through a microscope.

Let's take this same molecule of salt and break it down further. We know that salt is made of two elements, sodium and chlorine, and the chemist calls it sodium chloride. In breaking this molecule of salt into its two elements, we would then have one atom of sodium and one atom of chlorine. For a long time it was thought that the atom was the smallest unit of matter, but early in this century, the theory developed that all atoms were made up of tiny charges of electricity.

Each atom is made up of a nucleus or a fixed core. This nucleus is one or more positive charges called protons, and to complete the atom, this nucleus is surrounded by negative charges called electrons. In addition to central protons, some atoms have one or more neutral particles called neutrons.

While the neutrons and protons are stationary, the electrons are in constant rapid motion and are confined to their path by the attraction of the positive charged protons. This might be compared to the solar system with the proton and neutron representing the sun and the revolving electrons representing the planets. The atom is uncharged electrically as far as outside influence is concerned because protons and electrons are normally present in right quantity to neutralize one another.

Now how does this tie to electricity? We know that electrons are constantly traveling around at great speeds in the comparatively large space between the atoms. As you can imagine, they are constantly bumping into one another and some of the electrons are going to be thrown off their course and away from the original atom. These stray particles are called "free electrons" and it is the existence of these free electrons and their controlled flow that gives us electricity. Therefore, electricity is nothing but the flow of these free electrons.

Now let's look at some of the electrical quantities that we must define before we can make electrical calculations. We can compare an electric circuit to water flowing in a pipe. In both the water and electrical circuit, there are three quantities concerned in the operation of the circuit. They are pressure, current and resistance.

Pressure = Volt = "E"

Electricity or water cannot be made to flow unless one point has a higher value of pressure than the other. In the water system this pressure is measured in pounds per square inch, and in the electric system this pressure is called voltage and is measured in volts and is represented by the letter "E."

Current = Amperes = "I"

When water flows through a pipe, the question is not "How much water there is in the pipe" but rather "How much water is flowing through the pipe." The answer will not be "so many gallons," but "so many gallons per minute." That is, the time element must be considered, as we are interested in the rate of flow rather than the quantity.

In electricity, the unit current is called the "ampere." The number of amperes indicates the rate of flow of electricity through wires, just as the number of gallons per minute indicates the rate of flow of water through a pipe. The symbol used to represent the ampere is "I."

Resistance = Ohms = "R"

In the water circuit, friction retards the flow of water; in the electric circuit, a similar opposition to the flow of electric current exists, which in this case is called resistance. There is no definite unit of frictional resistance in the water circuit, but resistance in the electric circuit is expressed in terms of a difinite unit called the "ohm." Resistance is represented by the letter "R."

Power = Watts

The unit of electrical power is expressed in "watts." This is obtained by multiplying the value of electrical pressure (volts) by the value of current which produces useful work (some portion or all of the amperes). The watt is the rate of using electrical energy.

The watt is too small a unit for many commercial purposes, so the kilowatt is customarily used. A kilowatt is 1,000 watts.

There are three commonly used instruments for measuring the electrical units defined above. They are:

Ammeter

Ammeters are used to measure the rate of flow of electricity. The scale is usually marked to indicate the measurement in amperes, although when designed for circuits carrying very small currents, the scale is graduated to read in milliamperes(a milliempere is 1/1,000 ampere).

An ammeter is a low resistance instrument and must always be connected in series with the circuit and never across the line. When currents, which exceed the capacity of the meter are to be measured, only a portion of the current to be measured is passed through the ammeter, a ratio is established and the exact current is measured.

Voltmeters

Voltmeters are used to measure the voltage or the difference in electrical pressure between two points in a circuit. Voltmeters are connected across the line or across any two selected points and not in series with the circuit as in the case with the ammeter connection.

Voltmeters we use generally in industry are, in reality, ammeters and the deflection of the pointer is proportional to the flow of current thru the instrument. But unlike the ammeter, the voltmeter is a very high resistance instrument, with definitely known resistance connected in series with the operating circuit of the instrument. By proper calibration of the dial, correct voltage can be measured.

Wattmeter

A watt, as we have learned, is the unit of electric power and in direct current is the product of the volts times the amperes. In alternating current, the voltage times the amperes gives us the apparent power which does not equal the true power except in a purely resistance type circuit with unity power factor.

In the dynamometer type instrument, the stationary coil is used as a current coil in series with the circuit and the movable coil is used as a voltage coil and connected across the line. The current coil produces a magnetic field which is proportional to the amount of current flowing, and the voltage coil produces a magnetic field which is proportional to the voltage impressed across it. The force produced on the movable coil carrying the pointer is, therefore, proportional to the product of both the voltage and the current, or proportional to the power or wattage.

This wattmeter takes into account the power factor of the circuit and the reading we get is true power or voltage times amperes times power factor. At unity power factor, the current and the voltage are in phase and the current in both the movable potential coil and the stationary current coil reverse at the same time. The deflecting force is therefore always in the same direction.

When the voltage and the current are out of phase, there is an instant during each cycle when the current in one coil is reversed but the current has not yet reversed in the other coil. During this part of the cycle, there is a force tending to move the pointer in the other direction. However, the moving part of the meter has too much inertia to follow this rapid change and the pointer comes to rest in a position that indicates the resultant force, taking into account the phase relation between current and voltage.

Ohm's Law

In any electric circuit, the three factors of pressure, current and resistance are definitely inter-related. Thus, if the electrical pressure applied to a circuit is increased, more electrons will be set in motion and the current flowing in the circuit will be increased. Similarly, if the resistance to the flow of electrons is increased, that is by increasing the resistance of the circuit, and the applied voltage maintained at its original value, the flow of electrons—or electric current—would be reduced. And finally, if it is desired to maintain a given flow of electrons—or electric current—in a circuit whose resistance could be varied, then as the resistance is increassed, the voltage or electrical pressure would also have to be increased. These three statements may be rewritten in simplified form as follows:

1. Current varies with pressure (or voltage) when resistance is fixed.
2. Current varies in inverse proportion with resistance when pressure is fixed.
3. Pressure varies with resistance when current is fixed, or, more simply:

The current flowing in a circuit is equal to the electrical pressure divided by the electrical resistance.

This is known as Ohm's Law. Thus, if the voltage applied to a circuit and the resistance of the circuit are known, the amperes flowing can be found by dividing volts by ohms.

The law may be compactly stated in three forms:

Let I stand for the amperes flowing in the circuit, E stand for electrical pressure or voltage applied to the circuit, and R stand for the resistance of the circuit.

Then the law may be written as follows: $I = E/R$.

This expression is used when the volts and ohms are known and it is desired to find the current in amperes (Form 2) $E = IR$.

This expression is used when the amperes and ohms are known and it is desired to find the electrical pressure in volts. (The two letters IR written together mean I multiplied by R.) (Form 3) $R = E/I$.

This expression is used when the volts and amperes are known and it is desired to find the resistance in ohms.

Thus it is seen that if any two of the above quantities are known the third can be determined.

In practice, the two quantities usually known are the electrical pressure, measured in volts, and the current, measured in amperes. They are measured in amperes. They are measured with voltmeters and ammeters.

In every electric circuit there must be a complete path for the flow of the current. This path extends from one terminal of the source of supply (usually designated as the "positive" terminal), through one of the conducting wires, through the device or devices using the energy, through the other of the conducting wires to the second terminal of the source (usually designated as the "negative" terminal), and back through the source to the first (or positive) terminal.

There are two fundamental types of electric circuits known as the series circuit and the multiple or parallel circuit. Other types are a combination of these. The following discussion applies both to devices producing electrical energy (generators) and to devices receiving electrical energy (appliances).

Series Circuits

In a series circuit, all the parts that make up the circuit are connected in succession, so that whatever current passes through one of the parts passes through all of the parts.

The circuit shown in Figure 1 contains four resistances, R_1, R_2, R_3, and R_4, which are connected in series. The same current (1) flows through each of these resistances. Assume an electrical pressure (E) of 100 volts is applied across the terminals of the circuit, and that a current of 5 amperes flows through the circuit. By applying Ohm's law, the resistance (R) of the circuit as a whole is found to be 20 ohms; that is:

$R = E/I$ or 100 volts/5 amperes = 20 ohms.

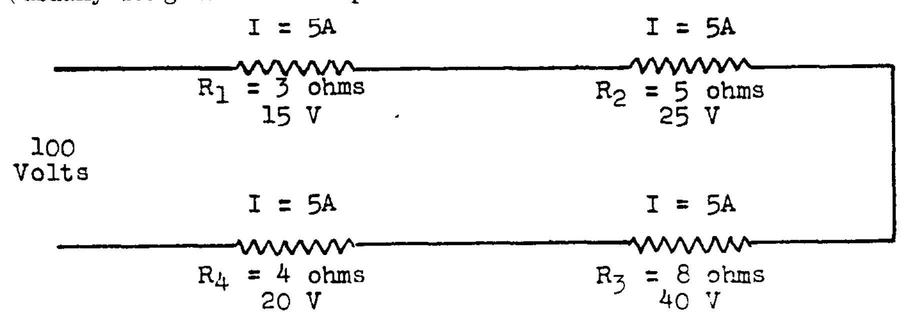
This total resistance is the sum of the resistances R_1, R_2, R_3, and R_4. The current of five amperes is the same throughout the circuit. The voltages across R_1, R_2, R_3, and R_4 are measured and found to be:

$E_1 = 15$ volts $\quad E_2 = 25$ volts

$E_3 = 40$ volts $\quad E_4 = 20$ volts

Now, Ohm's law applies to any part of the circuit as well as to the entire circuit. Applying Ohm's law to each resistance in the series circuit:

Since $E_1 = 15$ volts, $R_1 = E/I$
= 15 volts/5 amperes = 3 ohms.
$E_2 = 25$ volts, $R_2 = E_2/I$
= 25 volts/5 amperes = 5 ohms.
$E_3 = 40$ volts, $R_3 = E_3/I$



Fiig. 1—Simple Series Circuit.

$= 40$ volts/5 amperes $= 8$ ohms.

$E_4 = 20$ volts, $R_4 = E_4/I$

$= 20$ volts/5 amperes $= 4$ ohms.

As a check, it is found that the sum of the four individual voltages equals the total voltage:

$$E_1 + E_2 + E_3 + E_4 = E$$

15 volts + 25 volts + 40 volts + 20 volts = 100 volts.

Also, the sum of the separate resistance is equal to the total resistance; that is:

$$R_1 + R_2 + R_3 + R_4 = R$$

3 ohms + 5 ohms + 8 ohms + 4 ohms = 20 ohms.

When a current flows in a circuit, there is a continual drop in electrical pressure from one end of the circuit to the other. This drop is given by Ohm's law. It is $E = IR$ and is usually know as the IR drop. In all leads and connecting wire, this drop is kept as small as possible because it represents a loss.

In every appliance through which a current is sent there is also an IR drop, usually much larger than in the connecting wires because the resistance of the appliance is higher. If several appliances are connected in series, the electrical pressure does not drop evenly around the circuit but by steps, each step representing an appliance. Since the current is the same in all of them, the IR drop in each appliance is proportional to its resistance.

The generator or source of electrical pressure provides a certain total voltage for the circuit. Each appliance spends a part of it, but all these parts must add up to the original pressure or voltage.

Parallel Circuits

A multiple or parallel circuit is one in which all the components receive the full line voltage, the current in each part of the circuit being dependent on the amount of opposition (resistance) of that part of the circuit to the flow of electricity.

The circuit shown in figure 2 contains four resistances, R_1, R_2, R_3, and R_4, connected in multiple. Assume again that an electrical pressure (E) of 100 volts is applied across the terminals of the circuit. Here, each branch of the circuit receives the full voltage of 100 volts. Assume the resistances have the following values:

$R_1 = 1$ ohm, $R_2 = 4$ ohms,

$R_3 = 5$ ohms, $R_4 = 20$ ohms.

Again, applying Ohm's law to find the current flowing in each resistance:

Since $R_1 = 1$ ohm, $I_1 = E/R_1$

$= 100$ volts/1 ohm $= 100$ amperes

$R_2 = 4$ ohms, $I_2 = E/R_2$

$= 100$ volts/4 ohms $= 25$ amperes

$R_3 = 5$ ohms, $I_3 = E/R_3$

$= 100$ volts/5 ohms $= 20$ amperes

$R_4 = 20$ ohms, $I_4 = E/R_4$

$= 100$ volts/20 ohms $= 5$ amperes

The total current in a parallel circuit is equal to the sum of the separate currents:

$$I_1 + I_2 + I_3 + I_4 = I$$

100 amps + 25 amps + 20 amps + 5 amps = 150 amps.

The resistance of the entire circuit may be found by applying Ohm's law:

$R = E/I = 100$ volts/150 amps

$= 2/3$ or 0.667 ohm

Another way of obtaining the resistance of the entire circuit is to add the reciprocals of each of the resistances and taking the reciprocal of the sum (the reciprocal of a number is equal to 1 divided by the number); that is:

$$1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 = 1/R$$

1/1 ohm + 1/4 ohms + 1/5 ohms + 1/20 ohms = I/R

$$1.00 + 0.25 + 0.2 + 0.05 = I/R$$

Reciprocal of I/R is R or R = 1/1.50 = 0.667 ohm.

If resistances are connected in series, the ohms simply add up (as do the volts for generators connected in series), but, if they are connected in multiple it is observed that the resultant resistance is less than the smallest of the component resistances in the circuit. This is so because each additional resistance provides an additional path for the current, so that more current can flow. The conducting ability of the circuit is increased, the resistance is lowered.

It is also observed that connecting in series adds up the ohms (or volts); connecting in parallel adds up the amperes.

Series-Parallel Circuits

An example of resistances connected in series-parallel is given in figure 3 to get the total resistance of this circuit, the resultant resistance of each of the two parallel groups is first determined, then the resistances of groups 1, 2 and 3 are added. The same process applies to any number and kind of groups.

Power

When electricity is flowing into an electrical appliance, such as a lamp bulb, electrical energy is received by the lamp. The rate of transfer of electrical energy is called electrical power. The unit of electrical power is called the WATT: The watt is too small a unit for many commercial purposes, so the kilowatt is customarily used. A kilowatt is 1,000 watts.

In an electric circuit, there is an electrical pressure driving the electrons which corresponds to water pressure forcing water to flow through the pipe; this electrical pressure is measured in volts.

Also, in an electrical circuit, there is an electrical current which is pictured as so many electrons flowing past a point in the circuit each second, and this current is measured in amperes. That is, amperes in an electric circuit corresponds to the quantity of water per minute flowing in a pipe.

Similarly, therefore, in an electric circuit we obtain power by multiplying these quantities together:

Power = Electrical pressure x Quantity of electrons per second.

Watts ,(W) = Volts (E) x Amperes (I).

By experiment, it is found that there is a relationship between electrical power expressed in watts and mechanical power expressed in horsepower; one horsepower being equal to 746 watts.

1 HP = 746 watts.

This simply means that it takes 746 watts of electrical power to do the

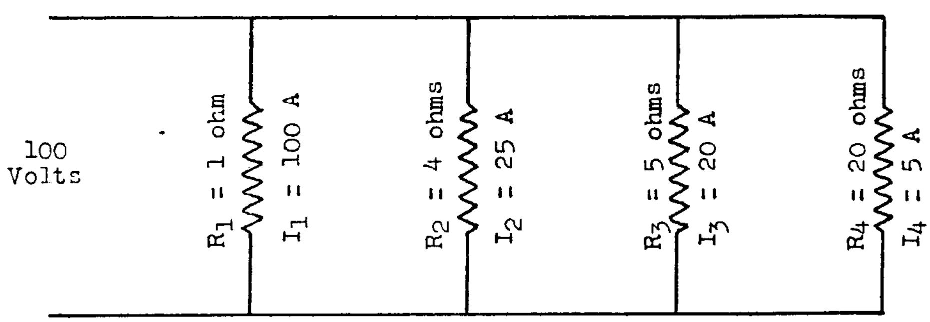


Fig. 2—Resistance in Parallel.

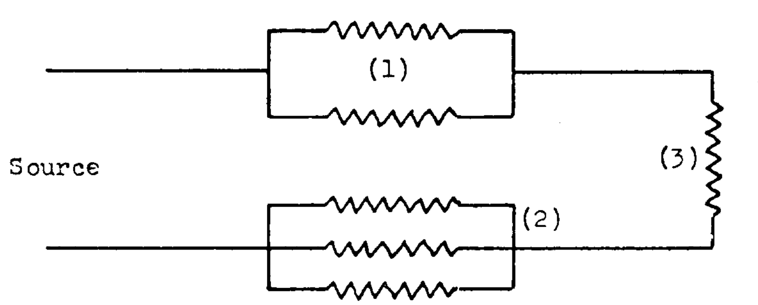


Fig. 3—Series - Parallel Circuit.

same work in the same time as one horsepower of mechanical power.

Energy

Since power is the rate of expending energy, that is, the energy expended in a given time (seconds, minutes, hours) then the total energy expended will be:

Energy = Power x time = E x I x T = Watts x time where T is the time in seconds, minutes or hours.

The unit of electrical energy most commonly used is the kilowatt-hour. This is what the house meters read.

Heat Loss

By Ohm's law, $E = IR$. If IR is substituted for E in the expression for power, $W = EI$ it becomes:

$W = I \times IR$

This may also be written $W = I^2R$ where I^2, or I squared, signifies I multiplied by itself, that is, I x I.

Therefore, if the current flowing through a circuit is known, as well as its resistance, it is possible to determine the power necessary to overcome the effects of the resistance. Where this power does not produce useful work, that is, where the electrical energy is not converted to some mechanical work, its is converted into heat and dissipated into the surrounding atmosphere. This heat, owing to the electrical resistance encountered, may be likened to the heat developed by friction, and represents a loss.

An example of such a condition, is the heat loss in the wires which carry the electric current from the generator to, let us say, an electric motor. In determining R, however, the resistance of the wires of the motor must be included, for there are losses in these as well as in any other wires.

If the current in a wire is DOUBLED, the heat loss is therefore QUADLUPLED (not doubled), if the resistance remains the same.

In transmitting electric power a great distance therefore two factors must be considered. First, the IR drop in the line must not be so great that the electrical pressure or voltage at the receiving end will be insufficient. Second, the I^2R power loss in the line must not be so great that it would be cheaper to carry fuel to the other end of the lines and set up a plant there.

In this limited time we have been able to touch on only the very basic electrical calculations, however the above formulas and examples are the basis for even the most complicated electrical problems. With what we have discussed you should be able to calculate and understand some of the electrical problems that you encounter in your electrified leases.