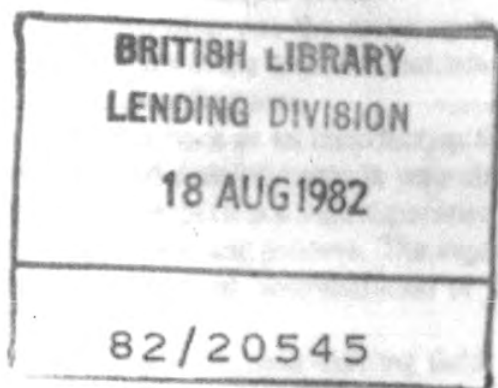


No. 1338
\$19.95

BASIC ELECTRONICS THEORY

-with projects & experiments

by Delton T. Horn



TAB **TAB BOOKS Inc.**
BLUE RIDGE SUMMIT, PA. 17214

FIRST EDITION

THIRD PRINTING

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Library of Congress Cataloging in Publication Data

Horn, Delton T.

Basic electronics theory—with projects & experiments.
Includes index.

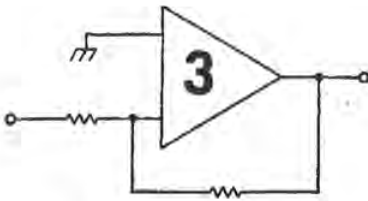
1. Electronics. 2. Electronics—Experiments.

I. Title.

TK7816.H69 621.381 81-9207

ISBN 0-8306-0020-5 AACR2

ISBN 0-8306-1338-2 (pbk.)



Alternating Current

So far we have been working with circuits where the current flows in only one direction. This form of electricity is called *direct current*, or *DC*.

Many other circuits, however, operate on a voltage and current that continuously vary in value, according to a repetitive, periodic pattern. Electricity in this form is called *alternating current*, or *AC*.

VARYING VOLTAGE AND CURRENT

The polarity of a voltage source determines the direction of current flow. The current will flow from the negative terminal of the voltage source to the positive terminal. If the polarity of the voltage source is reversed, the current will flow in the opposite direction.

Take a look at the circuit in Fig. 3-1. Here we have a circuit with two voltage sources, each a three volt battery. Since these batteries are connected with opposing polarities, if they were allowed to have an equal effect on the circuit, they would simply cancel each other out. No current would flow through the circuit, and the power consumed would be zero.

The two pots labelled R1 and R2 control the relative effect of the two batteries in the main circuit. The dotted line between these two schematic symbols indicates that they are mechanically tied together. That is, one knob controls both pots simultaneously. Such a multiple component is said to be *ganged*. Potentiometers can be dual, triple, or even quadruple ganged. Dual ganged pots are not uncommon, but larger combinations tend to be fairly rare.

For convenience in this discussion, we will refer to R1 and R2 as if they were a single potentiometer, since they always work in unison.

If the pot's slider is in the exact center of its path of rotation, equal resistances will be seen by each of the source voltages. So both batteries will present an equal, but opposite voltage to the main circuit. This results in the voltages cancelling each other out, and no current flows through the circuit.

If, however, the slider is moved all the way towards battery 1, that battery will see a minimum resistance, and battery 2 will see a maximum resistance. In other words, most of battery 2's voltage is dropped across the resistance of the potentiometer. But most of the voltage from battery 1 makes its way through to the external circuit. Therefore, as far as the load circuit is concerned, battery 2 doesn't exist. Battery 1 provides the power to operate the circuit.

At the other extreme of the slider's path, the situation is reversed—battery 2 is dominant, and battery 1 is ignored. At intermediate positions of the slider, the two voltages will interact in a subtractive manner. The battery closest to the slider will have the greater effect, but the other battery will cancel out some of the voltage.

For example, if the potentiometer is set so that 2.5 volts are passed from battery 1, while battery 2 is allowed to put out only 0.5 volts, the load circuit will see a voltage source of 2 volts (battery 1 - battery 2). This voltage will have the same polarity as the larger of the opposing voltages. In this case, battery 1 determines the polarity.

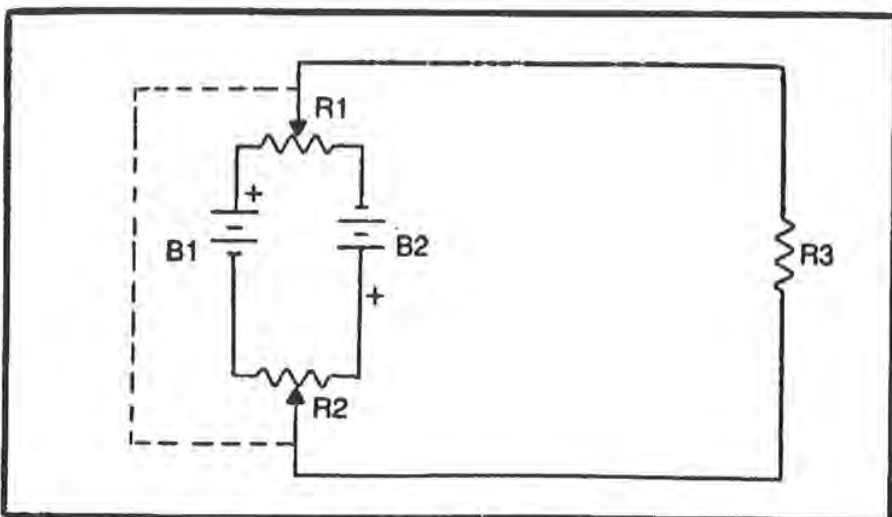


Fig. 3-1. A circuit that is powered by a voltage with reversible polarity.

If we draw a graph of the effective voltage seen by the circuit, as the potentiometer's slider is rotated through its entire range, it would look like Fig. 3-2.

Now, suppose we start with the slider in its center position, then smoothly rotate the knob back and forth. A graph of the effective voltage under these circumstances would resemble the one in Fig. 3-3.

Notice that there is a repeating pattern in this graph. If you happen to be familiar with trigonometry, you might recognize this graph as a series of representations of the function called the sine of an angle. For this reason, this *waveshape* is called a *sinusoidal*, or *sine wave*. Each complete pattern, without repetition (as from point A to point B in Fig. 3-3) is called a *cycle*, or a *wave*.

If you try a few Ohm's Law equations, you'll find that the current drawn by the circuit varies in step with the fluctuations of the applied voltage. When the voltage goes up, the current goes up, and vice versa. The current is said to be *in phase* with the voltage. A purely resistive circuit does not alter the phase relationship. When the voltage and current in a circuit fluctuate in this manner, we have an *Alternating Current*.

AC VOLTAGE SOURCES

Figure 3-4 shows the schematic symbol for any AC voltage source that generates a sine wave (other wave shapes will be discussed in later chapters). Notice, that since the current is constantly reversing itself, there is no fixed polarity for such a voltage source.

An AC source changes its polarity many times each second. By counting the number of complete cycles in a second, we get the *frequency* of the wave. Frequency is measured in *cycles per second* (cps). Another name for a cycle per second is *hertz* (Hz), named after a pioneer in the field. One thousand hertz is a *kilohertz* (kHz), or a *kilocycle per second* (kcps). Similarly, a million cps is one *megahertz*, or *megacycle*.

Typically, AC power sources operate at a fairly low frequency. In the United States, house current alternates at a 60 Hz rate. Other countries use a 50 Hz standard.

It might seem that using AC would just complicate matters, but actually, the reverse is true. While for low power applications it is easier to make DC devices (ie., batteries) than AC devices, in heavy wattage installations, AC is much more practical to generate. It is also easier to transmit AC over long lines. This is why the

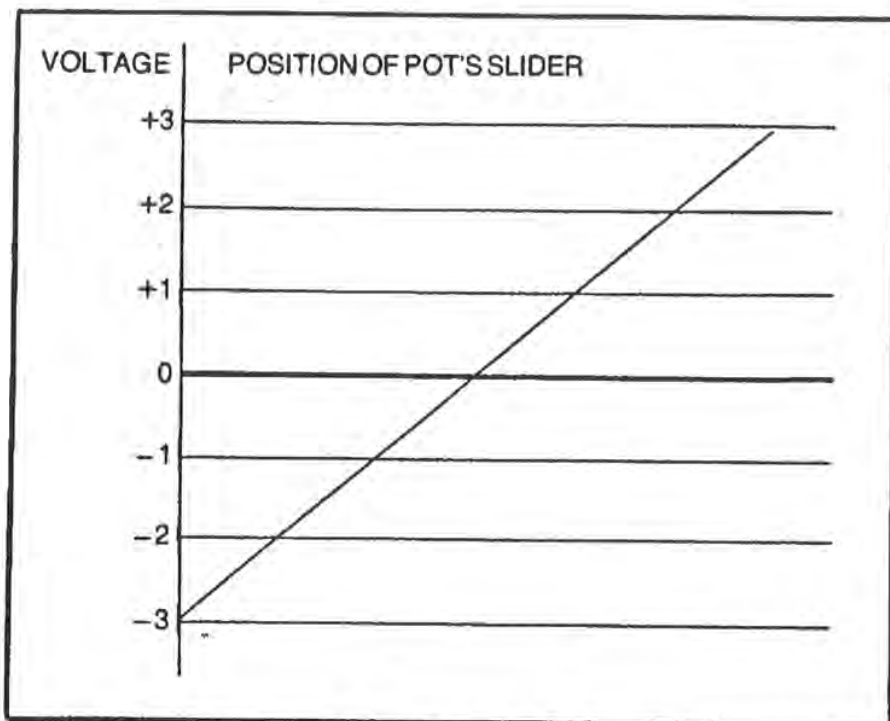


Fig. 3-2. The voltage through the circuit in Fig. 3-1 as the potentiometers are moved through their entire range.

electric power companies operate on AC. Also, as we shall see in later chapters, many circuits will operate quite differently depending on whether the electron flow through them is AC or DC.

The most readily available source of AC for powering electronic circuits, is the house current provided by the electric company through ordinary wall sockets (see Fig. 3-5). This is a power source of about 110 to 120 volts AC (the level fluctuates somewhat) with a nominal frequency of 60 Hz. This frequency also fluctuates slightly, but the average is usually a very precise 60 Hz.

Many electronic circuits are designed to operate directly from a AC wall socket, so the schematic includes a line cord. The symbol is shown in Fig. 3-6A. In other cases, the power is first passed through a *transformer* (see Chapter 7) to change the voltage, or

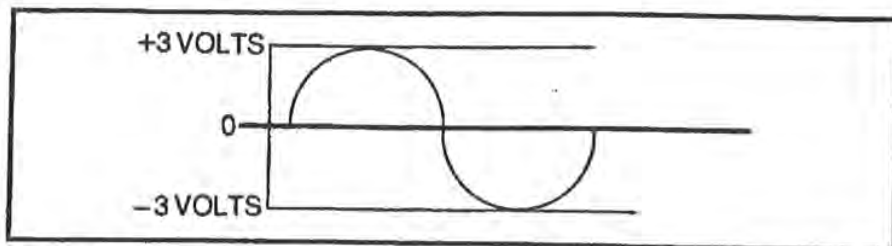


Fig. 3-3. A sine wave.

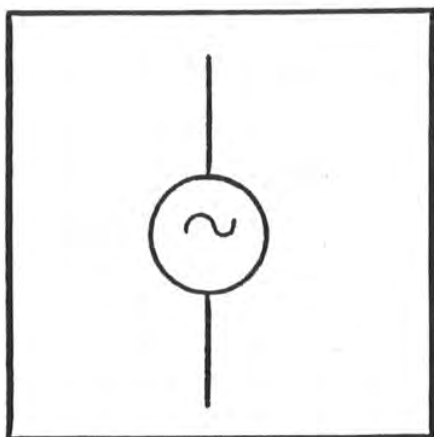


Fig. 3-4. Schematic symbol for an AC voltage source (sine wave).

through a power supply (see Chapter 26) to convert the AC to a DC voltage.

Many devices that operate off standard AC, also include an extra socket to carry the power on to other equipment. The schematic symbol for an AC socket is illustrated in Fig. 3-6B.

Notice that an AC line cord contains two wires. One is a reference line, and the other carries the actual current. With many circuits it doesn't matter which is which, but some circuits require that the power must come through the wires in a specific way. To insure that the cord is plugged into the wall socket properly, such

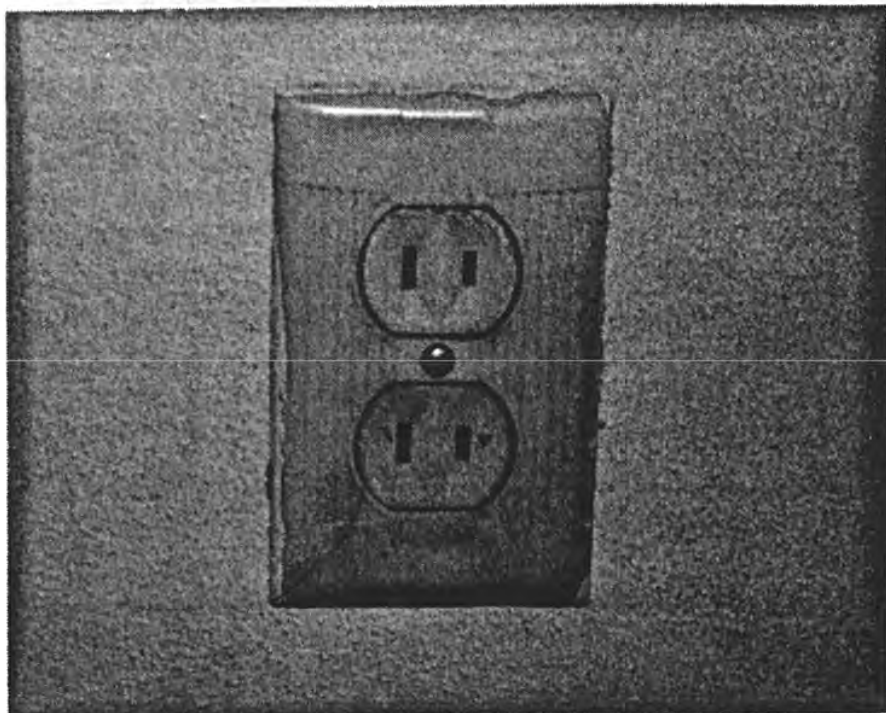


Fig. 3-5. An AC wall socket.

equipment uses a *polarized plug*. Such a plug can be plugged into the wall socket in only one way. If its prongs are reversed, it will not fit into the socket. A standard *non-polarized plug*, on the other hand can be reversed. Figure 3-7 shows the difference between a polarized and a non-polarized plug.

Sometimes, especially with equipment that draws heavy current levels (high wattage), extra protection is necessary—both for the circuit itself, and to prevent dangerous shock hazards to the user. In such equipment a third wire is needed to *ground* the circuit.

The word “ground” actually has two meanings in electronics. An *earth ground* offers protection by returning the voltage to the earth itself, via a metal post of some kind that makes a good contact with the ground. See Fig. 3-8. In this manner, any potentially dangerous voltage is shunted into the earth, rather than into the components of the circuit, or into the body of the operator. A cold water pipe is often a good place to make an earth ground connection.

For standard AC power, the screw in the center of the socket plate is connected to earth ground. In a three prong socket, the third prong is also connected to earth ground. When a device with a three prong plug must be used with a two prong socket, an *adapter*, such as shown in Fig. 3-9 is used. The wire *must* be connected to the center screw of the socket plate. Leaving this wire uncon-

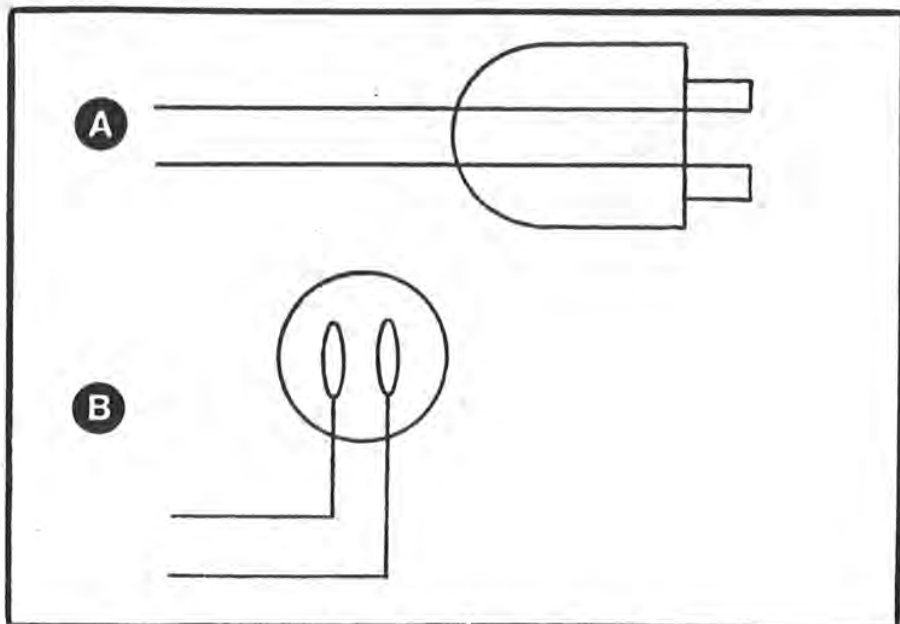


Fig. 3-6. Schematic symbols: A—AC line cord and B—AC socket.

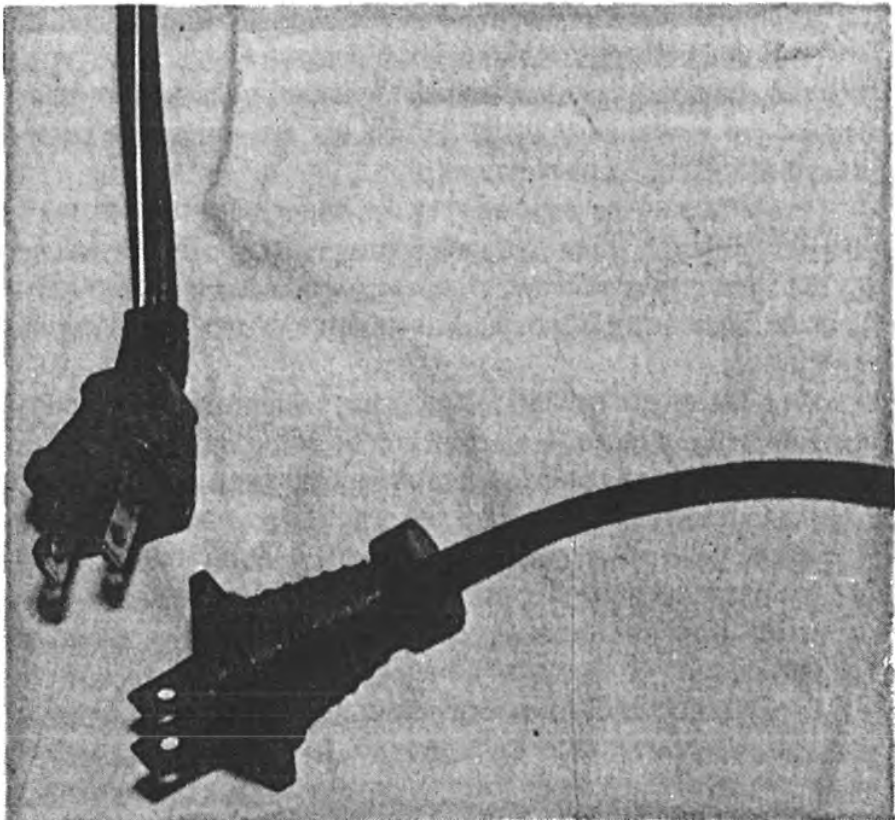


Fig. 3-7. Polarized and non-polarized line cords.

nected defeats the purpose of the third prong, and could be extremely dangerous!

The second kind of ground found in electronics work is also called a *common ground*, or simply *common*. This, as the name implies, is a point common to all signals in a circuit, so it is used as a reference point to measure voltages in the circuit.

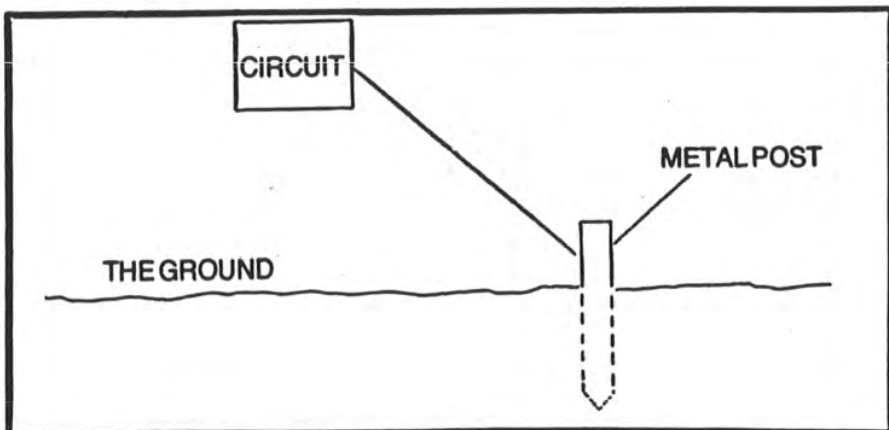


Fig. 3-8. Earth ground.

A common, by definition, is at 0 volts, so all other voltages can be measured between the appropriate point in the circuit and the common. In DC circuits the common point is usually either the negative terminal (somewhat more frequently) or the positive terminal of the voltage source. Either can be used without affecting circuit operation. It is just a reference point for measurements.

The type of common used will affect the polarity of the voltages measured. For example, in a circuit powered by a three volt battery with a negative ground, the source voltage will be + 3 volts. If a positive ground is employed, the source voltage is - 3 volts. This will not affect any circuit calculations as long as you are consistent throughout the circuit. If all voltages are of the same polarity, their signs can be ignored for calculations. If the voltage is negative, the current must be negative too. This means resistance will always work out to be positive ($R = E/I$).

In quite a few circuits, the common ground is attached to the metal chassis, or case of the circuit. When the common point covers a large area it is called a *ground plane*. Some circuits (especially *digital circuits*—discussed later) require a ground plane to avoid erratic operation.

Figure 3-10 shows the three most common schematic symbols for a ground point. The symbol at 3-10A is generally only used to indicate an earth ground, while the other two can represent either earth ground or common ground (sometimes also called *chassis ground*). In most cases when both types of ground are used, they are identical, ie., the same point, but this is not always true.



Fig. 3-9. AC three prong adapter.

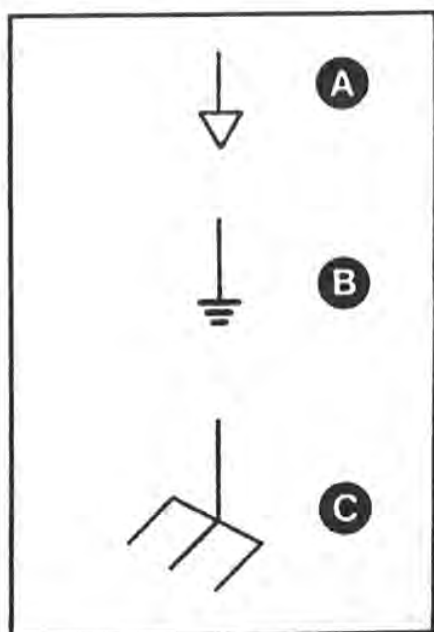


Fig. 3-10. Three common schematic symbols for a ground connection.

All points in a circuit with a ground symbol are electrically connected with all other similarly marked points. That is, the circuits in Figs. 3-11A and 3-11B are actually identical.

AC VALUES

Since the levels in an AC circuit are continuously changing, determining voltage and current values isn't the straight-forward matter it is with DC circuits. As an example, let's assume we have a sine wave that reaches a maximum, or *peak* value of 10 volts (it would also reach a negative peak of -10 volts). To say we have 10 volts AC is rather misleading, because the voltage actually reaches the full 10 volts for a brief instant during each cycle. The rest of the time, the voltage is lower.

Since the voltage varies between a 10 volt positive peak and a 10 volt negative peak, there is a 20 volt difference between the two peaks. That is, the voltage varies 20 volts *peak to peak*. While it is frequently useful to know this value, it would obviously be quite misleading to say that we had 20 volts AC.

It might seem that we could just take an average of the various instantaneous values passed through during the complete cycle, and come up with an average voltage. Unfortunately, since the positive portion of the cycle is a mirror image of the negative portion, *all* of the values are cancelled out, and we are left with an average voltage of zero.

A reasonable solution would be to take only half of the cycle—either just the positive portion, or just the negative portion—and take an average of that. This could be rather tedious to work out, but it has been mathematically proven that the average of half a cycle of a sine wave is always equal to 0.636 times the peak value. So, in our example, if the peak voltage is 10 volts, then the *average voltage* is 6.36 volts AC.

Conversely, if we know the average value, and need to find the peak voltage, we can multiply the average voltage times 1.572327. This can usually be rounded off to 1.57, or even 1.6.

While the average value can give us a fair idea of how much voltage is being passed through a circuit, a major disadvantage of using this kind of value is that the relationships stated in Ohm's

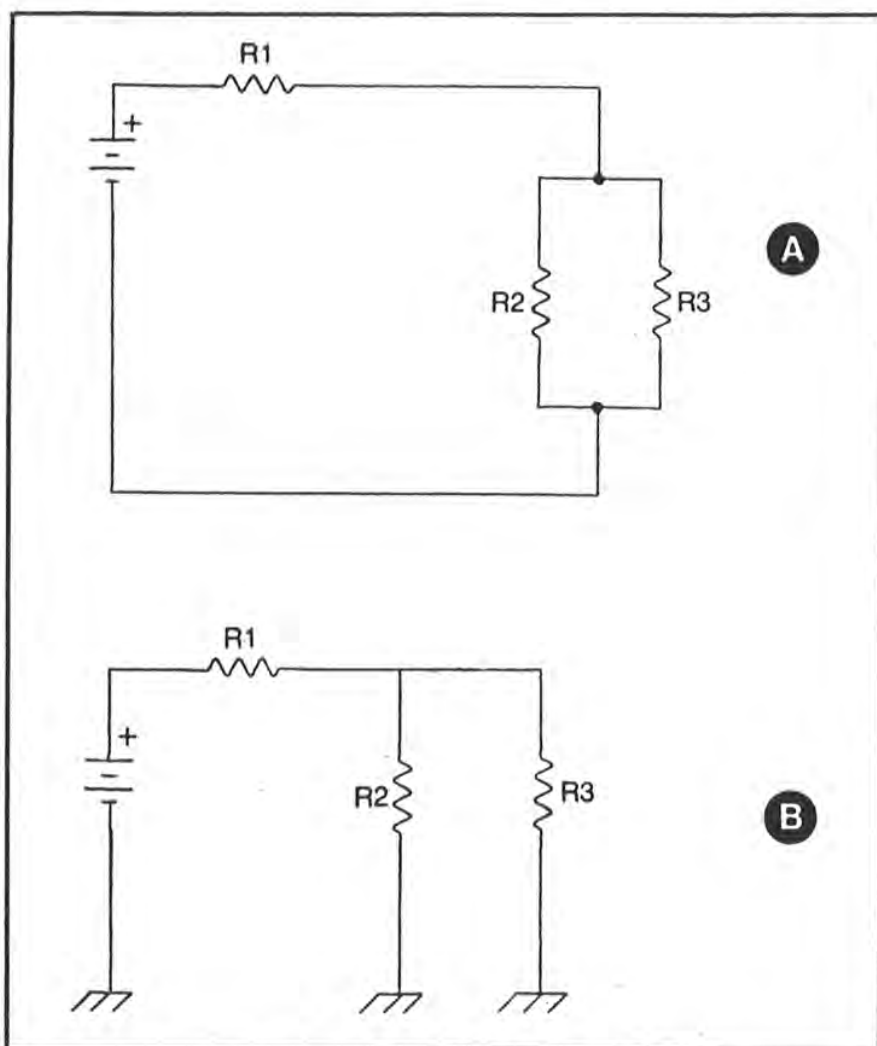


Fig. 3-11. Identical circuits, showing how the ground symbol is used.

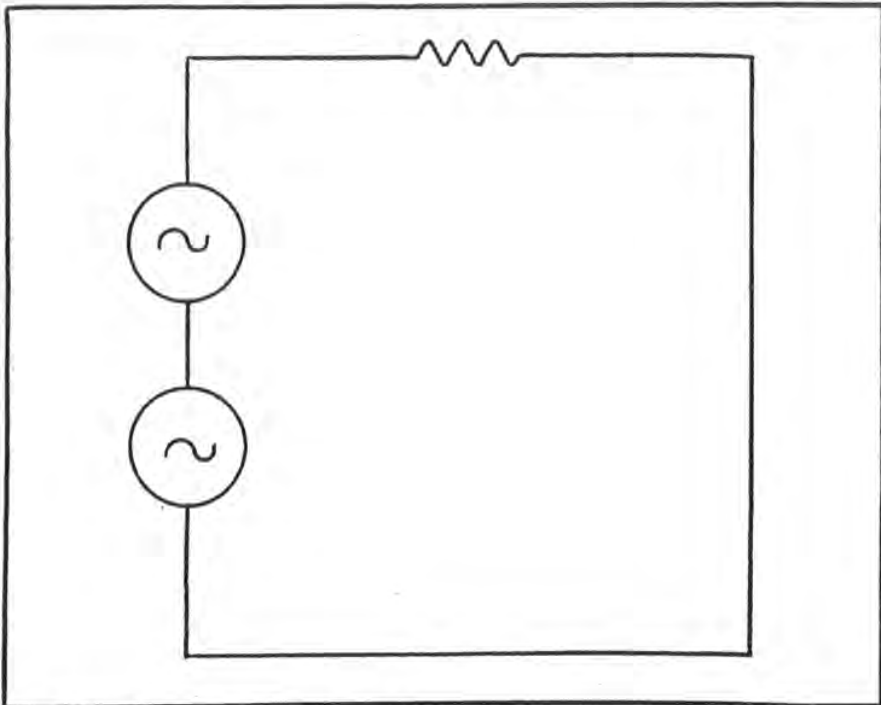


Fig. 3-12. Two AC sources in series.

Law no longer hold true. What we need is a way to express AC voltage in terms that can be directly compared to an equivalent DC voltage.

Such an equivalent value can be found by taking the *root-mean-square* of the sine wave. The mathematics are fairly complex, but it works out to 0.707 times the peak value.

In our example we have 10×0.707 , or 7.07 volts *rms*. This is the value most commonly used for AC measurements.

By using rms values, Ohm's Law can be used in the same way it is used with DC circuits.

Here is a summary of the basic AC equations.

$\text{RMS} = 0.707 \times \text{PEAK}$	Equation 3-1
$\text{RMS} = 1.11 \times \text{AVERAGE}$	Equation 3-2
$\text{AVERAGE} = 0.9 \times \text{RMS}$	Equation 3-3
$\text{AVERAGE} = 0.636 \times \text{PEAK}$	Equation 3-4
$\text{PEAK} = 1.41 \times \text{RMS}$	Equation 3-5
$\text{PEAK} = 1.57 \times \text{AVERAGE}$	Equation 3-6
$\text{PEAK TO PEAK} = 2 \times \text{PEAK}$	Equation 3-7

Equations 3-1, 3-5 and 3-7 are the most frequently used formulas. The average value is rarely of practical importance. The same equations are used for current and for power in AC circuits.

PHASE

The current from an AC voltage source is ordinarily in step with the voltage. That is, when the voltage increases, so does the current, and when the voltage decreases, the current also decreases. We say that the voltage and the current are *in phase*. Their cycles start at the same instant.

In later chapters we'll learn how some components can throw the voltage and current *out of phase*. That is, one is delayed so that the two are no longer in step with each other.

MULTIPLE AC SOURCES

Remember that when we have two or more DC voltages in series (such as cells in a battery), we can find the total voltage simply by adding the component voltages from each individual source. Or, if we have two voltages of opposite polarity, we can simply subtract the smaller from the larger to find the total effective voltage in the circuit. With AC sources, however, the situation is much more complex. If the two voltage sources in a circuit like in Fig. 3-12 are in phase with each other, there is no problem. We can simply add the voltages, just as with DC. Or, if the voltage sources are 180° out of phase with each other (one full cycle equals 360° —see Fig. 3-13), we can just subtract the smaller from the larger voltage. Of course, if two equal AC voltages are

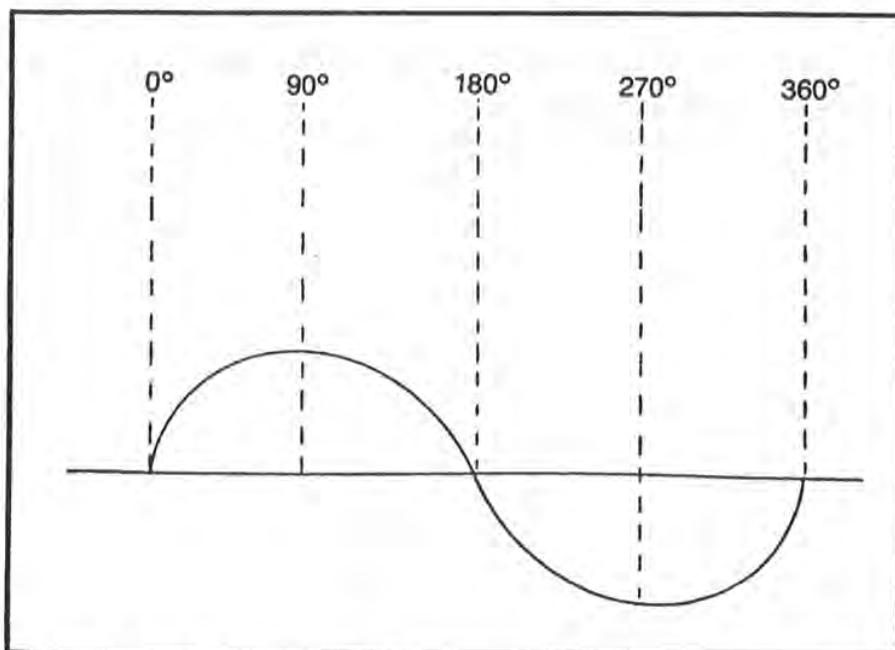


Fig. 3-13. The degrees of a cycle.

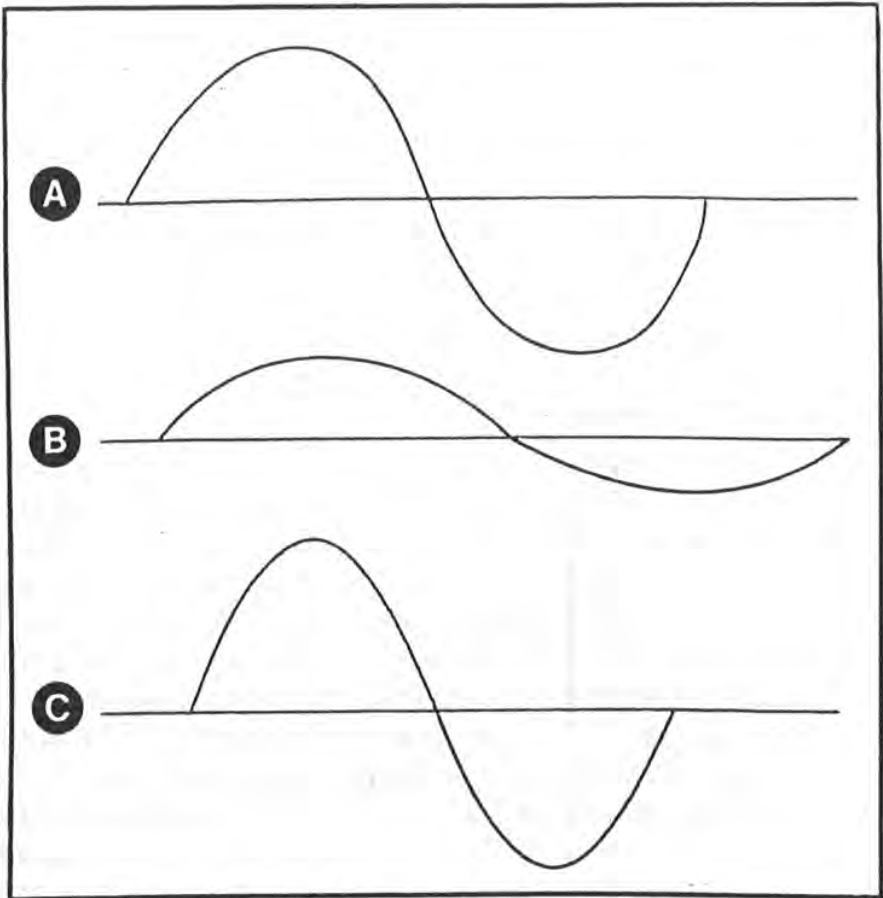


Fig. 3-14. Adding out of phase AC voltages.

180° out of phase with each other, they will cancel each other out, leaving a net voltage of zero.

To calculate any other phase relationship requires fairly complicated mathematics. For example, consider the graphs in Fig. 3-14. The voltage in graph B is 60° out of phase with the voltage in graph A. Graph C is the result of combining graphs A and B. Mathematically calculating the effective voltage shown in graph C would require numerous equations.

VECTOR DIAGRAMS

Fortunately, there is an easier way to solve combinations of out of phase AC signals. This is a method using *vector diagrams*. Vector diagrams may look and sound rather complicated, and the mathematical theory behind them is rather complex, but actually using these diagrams in practical situations is really quite simple. If you know how to use a ruler and a protractor, you should have no trouble.

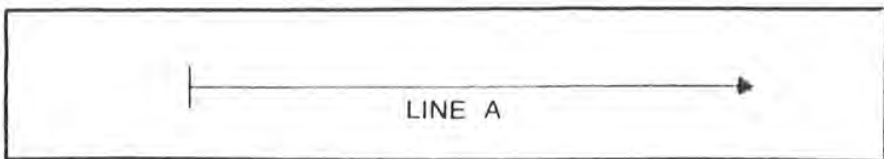


Fig. 3-15. Step 1 of a vector diagram.

Let's use a vector diagram to solve the resultant voltage in Fig. 3-14. Let's say, voltage A is 5 volts, and voltage B is 3 volts. Voltage B is 60° out of phase with Voltage A.

First draw a straight line to represent voltage A. You can use any scale you find convenient. For example, if you're using a scale of one inch equals one volt, line A should be five inches long. This step is illustrated in Fig. 3-15.

Now, starting at the point of origin of line A, draw a second line. This line represents voltage B, and it must be drawn to the same scale as line A (line B should be three inches long in our example). You also have to use your protractor to draw line B at an angle equal to its phase difference. Of course, line A is at 0° . In our example, line B should be at a 60° angle to line A. This is shown in Fig. 3-16.

Now draw a dotted line at a 90° angle at the open end of line A. Its length is unimportant, as long as it goes past line B. This is line C in Fig. 3-17.

Now, draw a fourth line (dotted line D in Fig. 3-18) from the open end of line B, so it intersects with line C at a 90° angle.

Finally, draw one last straight line from the junction of line A and line B to the junction of line C and line D. This is the line labelled E in Fig. 3-19. If we measure line E, it represents the resultant voltage, drawn to the same scale as lines A and B. In our

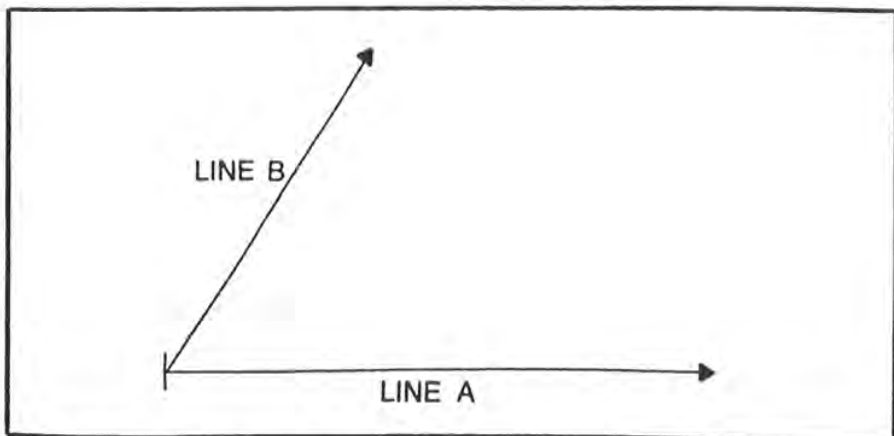


Fig. 3-16. Step 2 of a vector diagram.

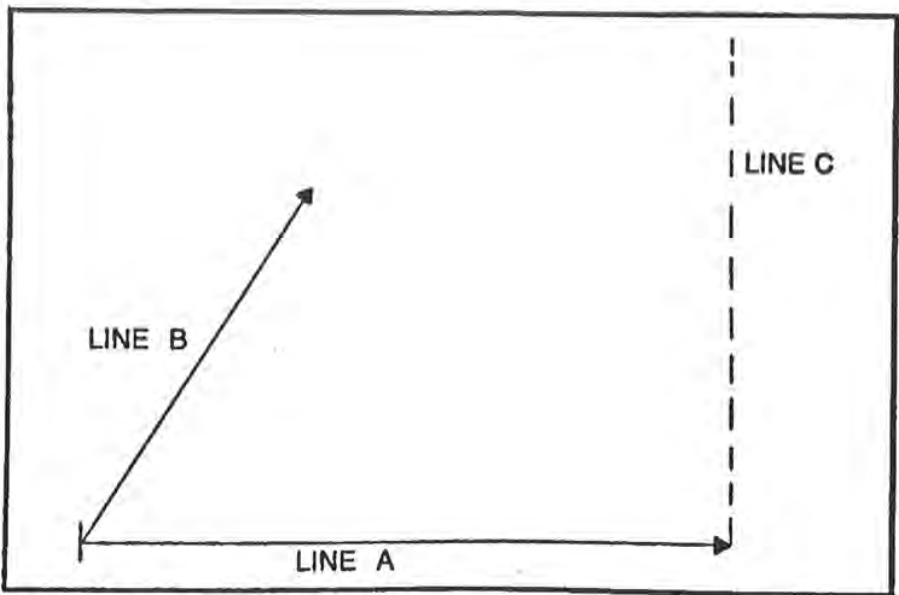


Fig. 3-17. Step 3 of a vector diagram.

example, it comes out to 5.5 volts. The angle of line E is the same as the phase angle of the resultant voltage.

Additional examples of vector diagrams are shown in Figs. 3-20 and 3-21. Try drawing vector diagrams to solve for the resultant voltage for each of the combinations shown in Table 3-1.

COMBINING AC AND DC

What happens when you have a circuit with both a DC voltage source and an AC voltage source, like the one in Fig. 3-22? Let's

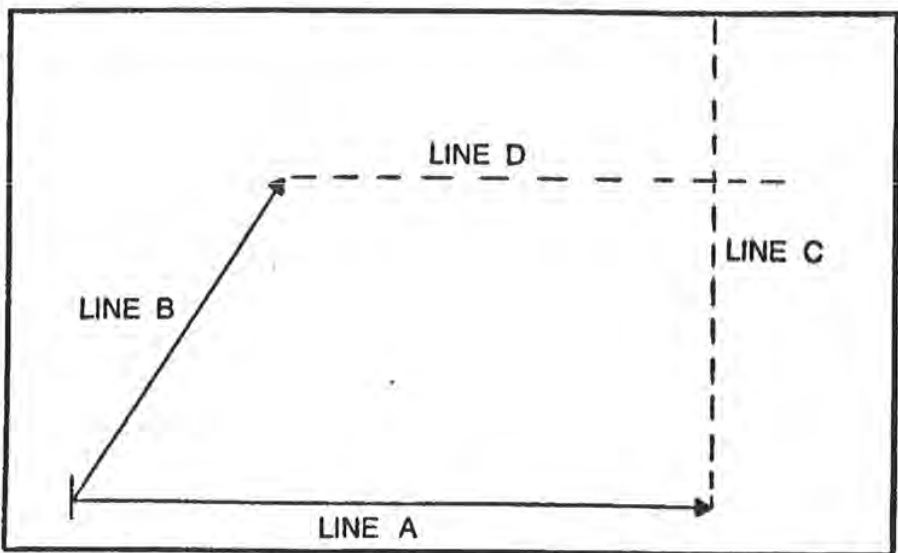


Fig. 3-18. Step 4 of a vector diagram.

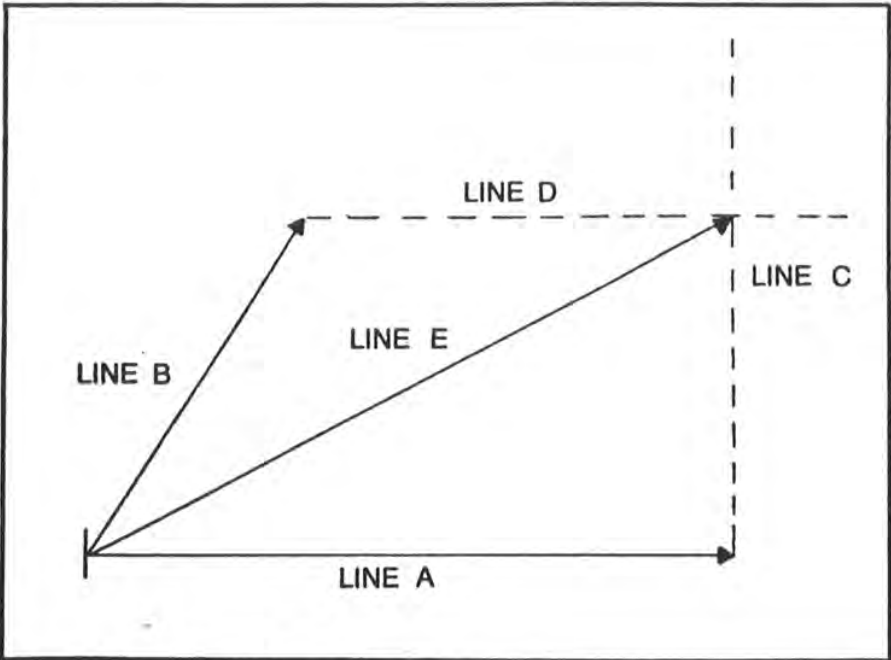


Fig. 3-19. The completed vector diagram.

assume the AC puts out a 5 volt peak sine wave, and the DC source is 9 volts. At any given instant, the AC signal has a specific value. For instance, whenever the signal crosses the 0 line, it has an instantaneous value of 0 volts. At this instant, the AC source has no effect on the circuit—the total circuit voltage at this brief point in time is simply the 9 volts from the DC source.

However, at another instant in its cycle, the AC source is putting out its peak value of 5 volts. Meanwhile, the DC source is still producing 9 volts. These values are simply added, and the instantaneous value is 14 volts. When the AC voltage reaches its

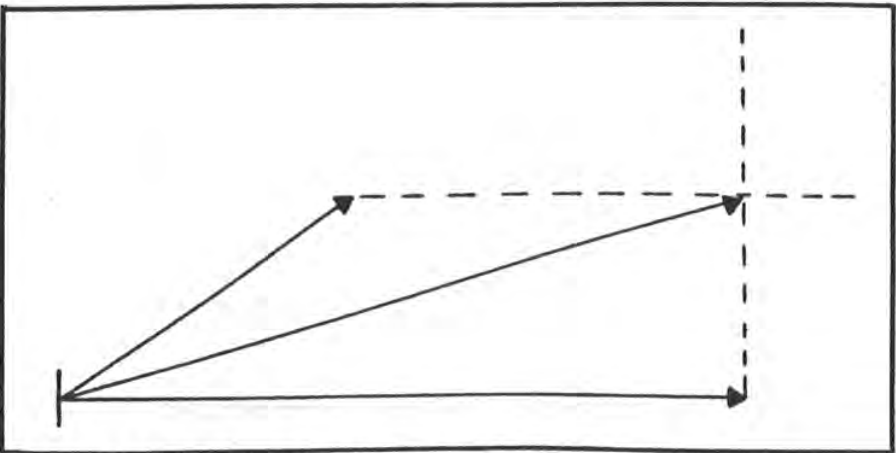


Fig. 3-20. Additional sample vector diagram.

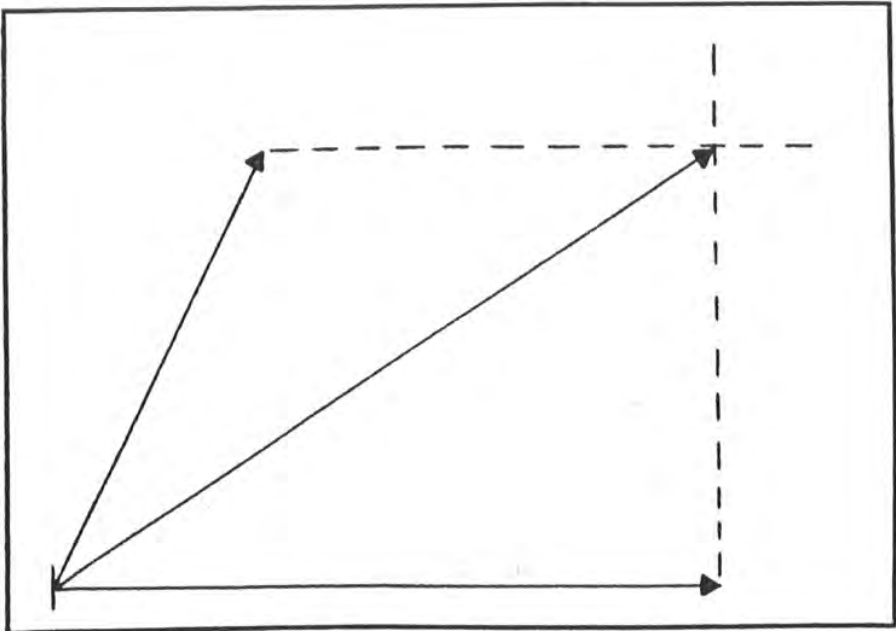


Fig. 3-21. Additional sample vector diagram.

negative peak (-5 volts), the polarity opposes that of the 9 volts DC source. In this case we have -5 volts and $+9$ volts, so the instantaneous value is $+4$ volts.

If we continue figuring the instantaneous values at various points throughout the cycle, we will find we have a sine wave that varies between $+4$ volts and $+14$ volts. The graph of the resultant

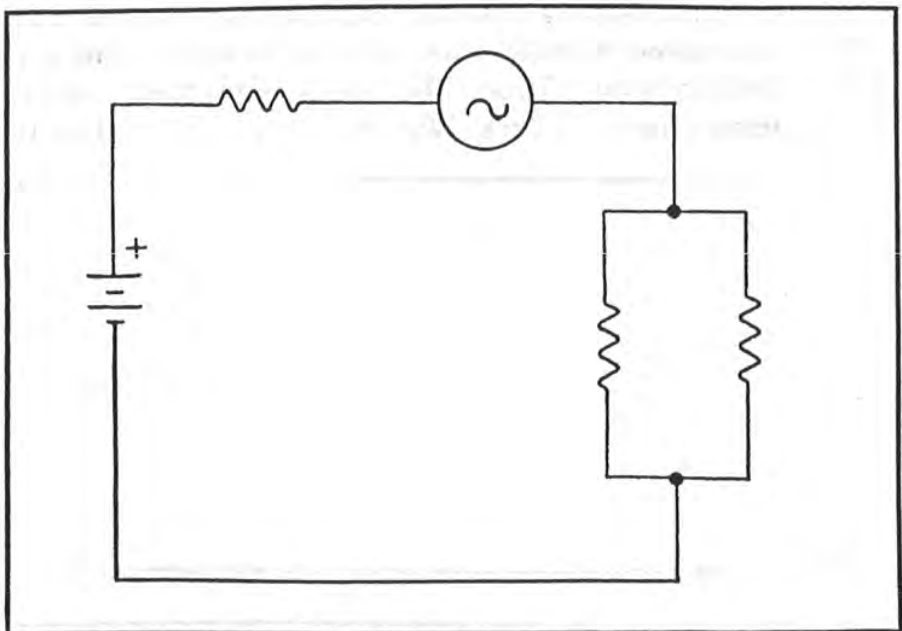


Fig. 3-22. A circuit with both AC and DC voltage sources.

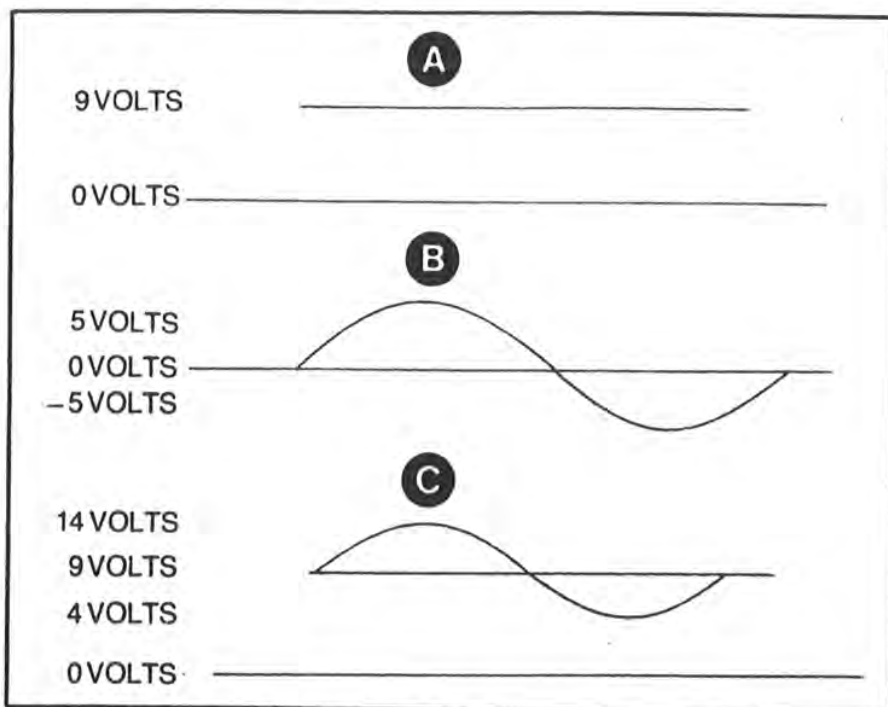


Fig. 3-23. Combining AC and DC voltages.

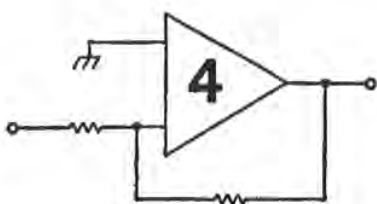
voltage is shown in Fig. 3-23. Notice that it is identical to an ordinary sine wave, except it varies above and below nine volts, rather than zero volts. We say we have 3.535 volts AC rms (5 volts peak) *superimposed* on 9 volts DC.

Table 3-1. Values for Practice Vector Diagrams.

VOLTAGE A	VOLTAGE B	PHASE
6	6	45°
8	3	90°
7	5	30°

If the AC voltage peak is less than the DC voltage, circuit polarity will not be reversed at any time in the cycle. If, on the other hand, the AC voltage is larger than the DC voltage, then polarity will be reversed during at least some of the cycle. For example, 10 volts AC peak superimposed on 6 volts DC will produce a combined voltage that fluctuates between -4 volts and +16 volts.

In solving most circuit equations, the AC and DC elements are handled separately. In many cases, one or the other can be ignored without adversely affecting our understanding of circuit operation.



Capacitance

It was mentioned in Chapter 2 that the most commonly used component in electronic circuits is the resistor. Probably the second most commonly used component is the *capacitor*.

WHAT IS CAPACITANCE?

If two metal plates are separated by an insulator (or *dielectric*), and a DC voltage is applied between the plates, current will not be able to cross the dielectric. But a surplus of electrons will be built up on the plate connected to the negative terminal of the voltage source, while there will be a shortage of electrons on the plate connected to the positive terminal. The voltage source will try to force electrons into one plate (negative terminal) and draw them out of the other (positive terminal).

At some definite point, these plates will be completely saturated. No further electrons can be forced into the negative plate, and no more electrons can be drawn from the positive plate. At this point, the plates have an electrical potential equal to that of the voltage source. In fact, the plates now act like a second voltage source in parallel with the first, and with the opposite polarity. Figure 4-1 shows the equivalent circuit. Naturally, since these opposing voltages are equal, they cancel each other out and no current can flow between the voltage source and the plates in either direction. The plates are said to be *charged*.

Now, if the voltage source is removed from the circuit, as in Fig. 4-2, the plates will stay charged, because there is no place for the electrons on the negative plate to go. Similarly, there is no

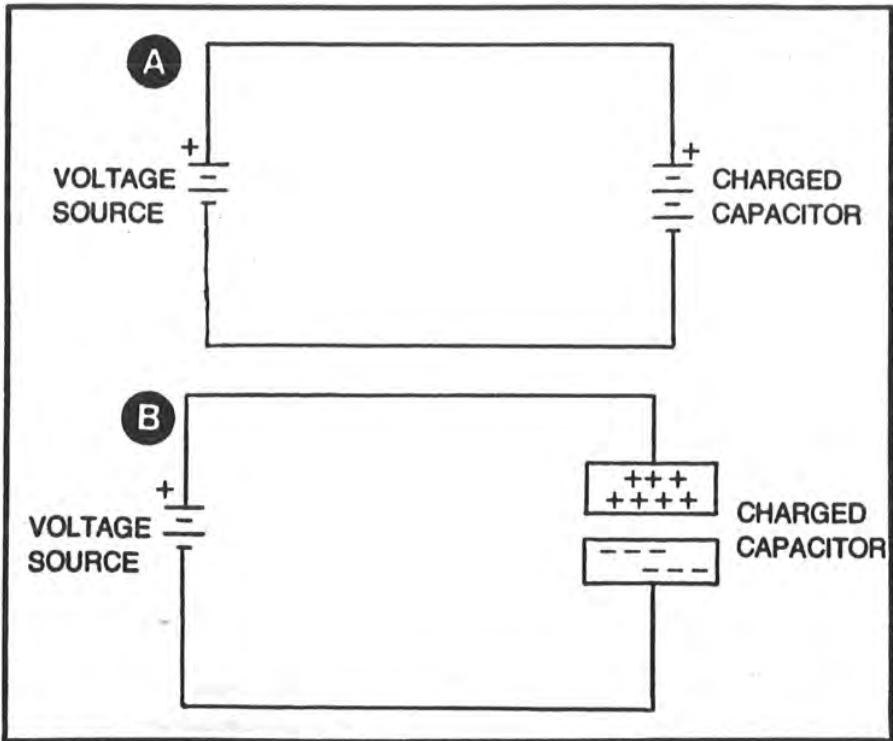


Fig. 4-1. Equivalent circuits for a charged capacitor.

place for the positive plate to draw electrons from. The voltage is stored by the plates.

Replacing the missing voltage source with a resistor, as shown in Fig. 4-3 provides a current path for the excess electrons stored on the negative plate to flow to the positively charged plates. This will continue until both plates are returned to an

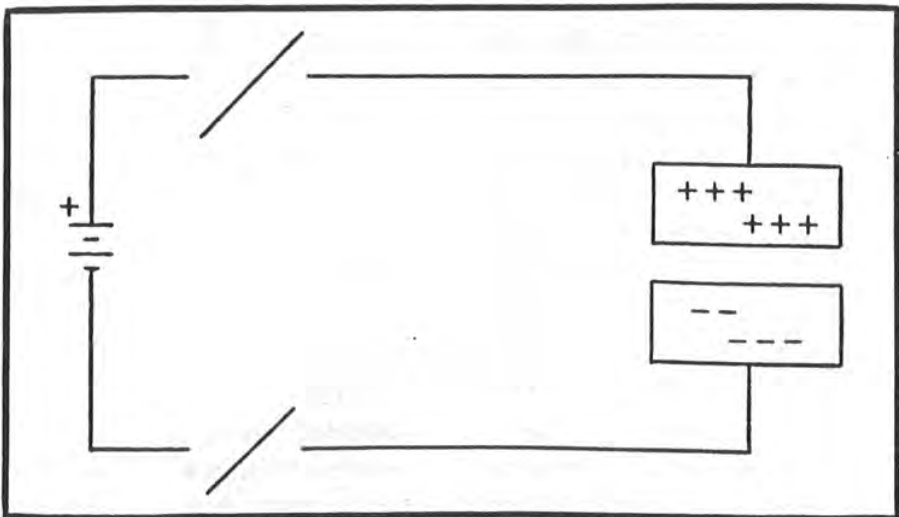


Fig. 4-2. Charged capacitor removed from power source.

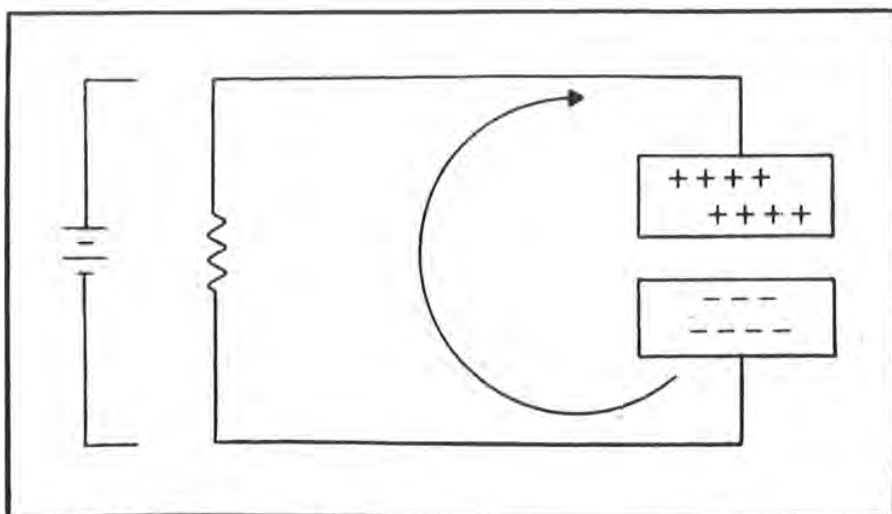


Fig. 4-3. Discharging a capacitor.

electrically neutral state. This process is called *discharging* the plates.

Such a device (two conductive plates, separated by insulator) is called a *capacitor*. A capacitor is used to store electrical energy. At one time capacitors were known as *condensers*, but this term is somewhat misleading and has fallen largely into disuse. You may, however, run across it once in a while. Just remember, it is simply another name for a capacitor.

A capacitor can not hold a charge indefinitely. Even air can conduct some current, so the charge will slowly seep off into the air. This is a form of *leakage*. There will also be some leakage through the insulating dielectric. Of course, if all other factors are equal, the lower the internal leakage, the better the capacitor.

Now, let's consider what happens in a capacitor when an alternating current is applied to it. See Fig. 4-4. During the first part of the cycle, as the source voltage increases from zero, it will charge the plates of the capacitor in a manner similar to the DC circuit described above. The polarity of the charge capacitor opposes that of the source voltage.

The capacitor may or may not be completely charged by the time the applied voltage passes its peak and starts to decrease again (this will depend on the size of the plates, how much voltage is applied, and the frequency of the AC signal).

In either case, as the applied voltage decreases, a point will be reached when it is less than the charge stored in the capacitor. This will allow the capacitor to start discharging through the AC voltage source.

The capacitor may or may not be completely discharged when the AC voltage reverses polarity, but since the source polarity is the same as the capacitor polarity, the voltages aid, quickly discharging the capacitor the rest of the way, then charging it with the opposite polarity from the original charge. When the AC source voltage reverses direction, the capacitor is discharged again, and the entire process is repeated with the next cycle of the AC waveform.

If you constructed the circuit illustrated in Fig. 4-5 with a DC voltage source, the lamp would not light, because the DC current can not flow through the circuit—it is blocked by the dielectric. The capacitor acts like an open circuit as far as direct current is concerned.

If, however, the same circuit is built with an AC voltage source, the lamp will light. See Fig. 4-6. This indicates that alternating current is flowing through the circuit. Of course, virtually no current (except the tiny leakage current) will flow across the dielectric itself. Remember, any given electron doesn't travel very far in an electric circuit. It merely moves far enough to disturb its neighbor. The process of charging, discharging, and recharging a capacitor from an AC voltage source, gives the same effect as if the current was actually flowing through the capacitor

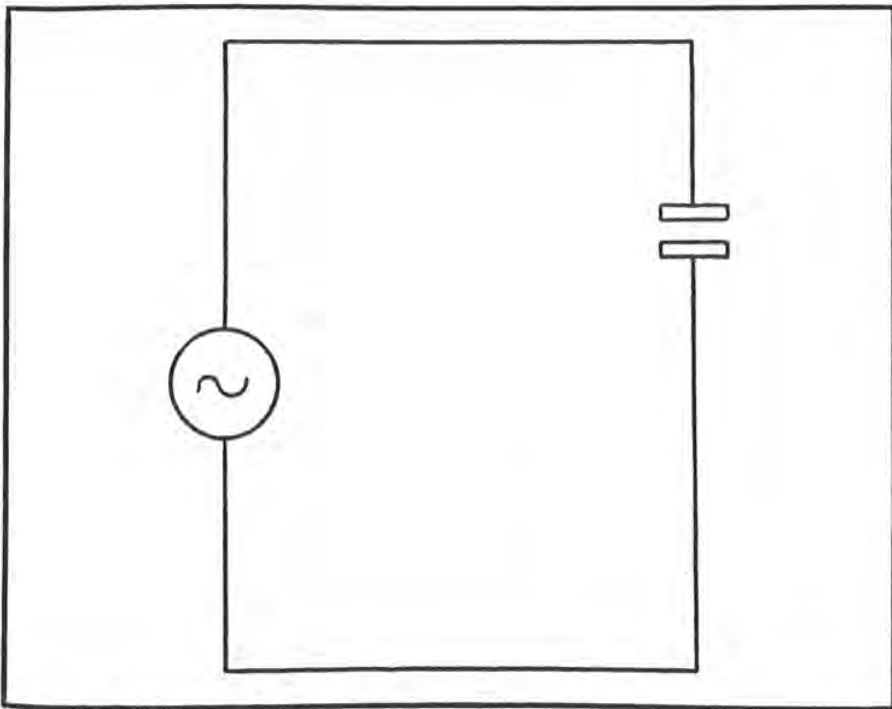


Fig. 4-4. Capacitor in an AC circuit.

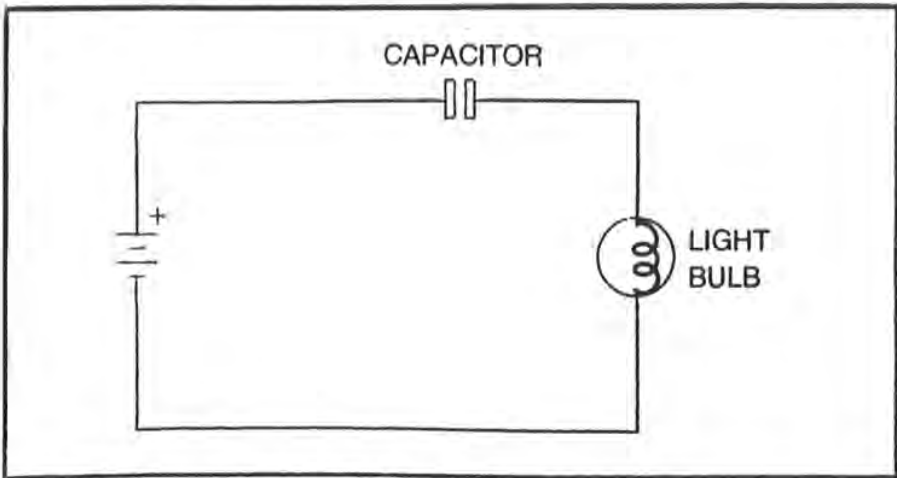


Fig. 4-5. Circuit to test current flow through a capacitor.

itself. Moreover, if we decrease the frequency of the AC source, the lamp will dim. Increasing the frequency will cause the lamp to burn brighter. A capacitor lets more current flow as the frequency of the source voltage is increased.

If we measured the DC resistance of a discharged capacitor, the meter's needle would show a sharp kick down to a moderately low resistance as the capacitor is charged. Then it will settle down to a very high resistance value. In an ideal capacitor we would have an infinite resistance, ie., a completely open circuit.

However, we've already indicated that AC can flow through a circuit with a capacitor. The apparent resistance of a capacitor in an AC circuit is less than its DC resistance. This apparent AC resistance is called *capacitive reactance*. Its value decreases as the applied frequency increases. A capacitive reactance slows down voltage more than it does current, so the voltage lags the current by 90° (assuming a purely capacitive circuit).

Before we can present the formula for determining capacitive reactance, we need to know how capacitance is determined. The basic unit of capacitance is the *farad*. If one ampere of current flows when the applied voltage changes at a rate of one volt per second, we have one farad of capacitance (1 F).

In actual circuits, the farad is far too large a value. Instead, we generally use the *microfarad* which is one millionth of a farad. The microfarad can be abbreviated either as μF or mF. The first abbreviation is generally preferred today. A still smaller unit is the *picofarad* (pF), which is one millionth of a microfarad. Sometimes a picofarad is referred to as a *micromicrofarad* ($\mu\mu\text{F}$ or mmF).

Capacitance can be increased by making the metal plates larger, or by bringing them closer together or, in other words, making the dielectric thinner.

The specific dielectric used also has an effect on the capacitance of the unit. Air, for example, has a *dielectric constant* (K) of one. Mica, however, has a dielectric constant of six. Paper is between two and three, and titanium oxide can have a dielectric constant as high as one hundred and seventy.

Capacitance (in picofarads) can be calculated with the following formula:

$$C = \frac{0.0885 \times K \times A}{T} \quad \text{Equation 4-1}$$

A represents the area of the side of one of the plates that is actually in physical contact with the dielectric. This area is measured in square centimeters for this equation. T represents the thickness of the dielectric (or the space between the plates), and is also measured in centimeters. K , of course, is the dielectric constant.

Let's assume we have a capacitor where $A = 35$ square centimeters, and $T = 2$ centimeters, and the dielectric is air ($K = 1$). Algebraically we have $C = (0.0885 \times K \times A)/T = 0.0885 \times 1 \times 35/2 = 3.0975/2 = 1.54875$, or about 1.5 pF.

If, however, the dielectric is changed to mica ($K=6$), and all other variables are the same, we find that $c = (0.0885 \times K \times A)/T = 0.0885 \times 6 \times 35/2 = 18.585/2 = 9.2925$, or approximately 9 pF.

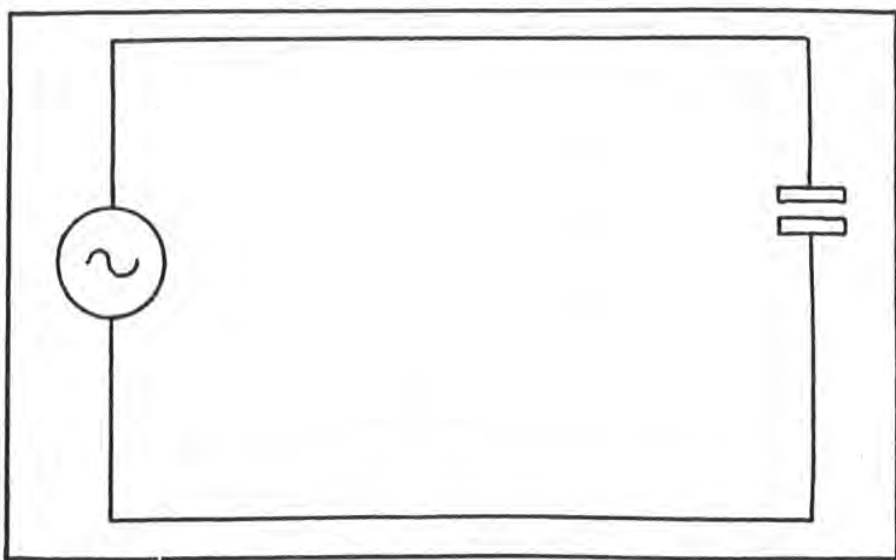


Fig. 4-6. AC capacitor circuit.

Now, let's try increasing T to 5. $C = (0.0885 \times 6 \times 35)/5 = 18.585/5 = 3.717$, or just under 4 pF. Increasing T decreases the capacitance, while increasing K increased the capacitance. The capacitance will also increase with an increase in A . For example, we can change A to 50 square centimeters. Then, $C = (0.0885 \times 6 \times 50)/5 = 26.55/5 = 5.31$, or just over 5 pF.

As one final example, let's see what happens when the dielectric constant is increased by a very large amount. We'll replace the mica ($K=6$) with titanium oxide ($K=170$). Now the equation comes out to $C = (0.0885 \times K \times A)/A/T = (0.0885 \times 170 \times 50)/5 = 752.25/5 = 150.45$, or approximately 150 pF.

Now, assume you have a capacitor that uses paper as a dielectric ($K=2.5$). $A = 90$ square centimeters, and $T = 3$ centimeters. What is the capacitance?

In actual practice, you will rarely need to use this formula, unless you are manufacturing capacitors, but it is helpful to understand how the variables interrelate in determining capacitance.

Returning to capacitive reactance, its value is determined by the capacitance and the frequency of the applied AC voltage. Reactance is stated in ohms, like ordinary DC resistance. The formula is as follows,

$$X_c = \frac{1}{2\pi FC} \quad \text{Equation 4-2}$$

In this equation, F stands for the frequency (in hertz), and C represents the capacitance in farads (*not* in microfarads or picofarads). The symbol π is the Greek letter pi, and it is used in many formulas to represent a universal constant. The value of pi is always approximately 3.14, so $2 \times \pi =$ about 6.28. This means the formula can be rewritten as $X_c = 1/(6.28 \times F \times C)$.

Notice that the applied frequency is 0 (that is, DC) the value of the denominator becomes 0, regardless of the capacitance value, since zero multiplied by any number always equals zero. $1/0$ is unsolvable—it equals infinity. Infinite resistance in a circuit, of course, acts like an open or incomplete circuit. This is exactly the way a capacitor behaves in a DC circuit.

Let's try a few examples with AC frequencies. We'll start with a $1 \mu\text{F}$ (1×10^{-6} Farad) capacitor. The denominator equals $2\pi FC$, which we can rewrite as $6.28 \times (1 \times 10^{-6}) \times F$, or $6.28 \times 10^{-6} \times F$, so the reactance equation for a $1 \mu\text{F}$ capacitor is $X_c = 1/(6.28 \times 10^{-6} \times F)$.

If F is 10 Hz, we find that $X_c = 1/(6.28 \times 10^{-6} \times 10) = 1/(6.28 \times 10^{-5})$, or about 16,000 ohms (16K). If F is increased to 50 Hz, $X_c = 1/(6.28 \times 10^{-6} \times 50) = 1/(3.14 \times 10^{-4})$, or approximately 3,200 ohms (3.2K). If F is 600 Hz, then $X_c = 1/(6.28 \times 10^{-6} \times 600) = 1/(3.768 \times 10^{-3})$, or about 265 ohms.

You can clearly see that when the capacitance remains constant, and the frequency increases, the reactance decreases. Additional examples are given in Table 4-1.

OHM'S LAW AND REACTANCE

Ohm's Law works with reactance in exactly the same way it does with regular DC resistance. The only difference that you must keep in mind is that the result of any specific equation is true only for a single, specific frequency.

For an example, we'll consider the circuit shown in Fig. 4-6, which consists of just a capacitor and an AC voltage source. For the sake of simplicity, we'll be considering only reactance. In this simple case, the effects of regular resistance can be considered minimal. In most practical circuits, however, both resistance and reactance would have to be considered. We'll see how this is done later.

We'll assume the capacitor has a value of $1 \mu\text{F}$, so we can use the reactance values found in the examples in the last section. We'll also assume the AC voltage source generates 100 volts rms. According to Ohm's Law, the current equals the voltage divided by the resistance, or, in this case, the voltage divided by the reactance. At 10 Hz, we know that a $1 \mu\text{F}$ capacitor has a reactance of about 16,000 ohms. $I = E/X_c = 100/16,000 = 6.25 \times 10^{-4}$ amperes, or 0.625 mA. This could also be written as 625 μA . When the frequency is increased to 50 Hz, the capacitive reactance drops to about 3,200 ohms. $100/3200 = 3.125 \times 10^{-3}$ amperes, or

Table 4-1. Capacitive Reactance Samples.

CAPACITANCE	FREQUENCY		
	10Hz	100Hz	1000 Hz
0.001 μF	16 megohms	1.6 megohms	160 kilohms
0.01 μF	1.6 megohms	160 kilohms	16 kilohms
0.1 μF	160 kilohms	16 kilohms	1600 ohms
1 μF	16 kilohms	1600 ohms	160 ohms
10 μF	1600 ohms	160 ohms	16 ohms
100 μF	160 ohms	16 ohms	1.6 ohms

about 3 mA. At 600 Hz, the reactance is a mere 265 ohms, so $I = 100/265 = 0.38$ amperes, or 38 mA. Notice that as the frequency goes up, the current also increases, while the reactance value goes down.

According to Ohm's Law, current and resistance are always in an inverse relationship to each other. When one increases, the other decreases. Now, assume the voltage source generates 24 volts rms, and the capacitor is $0.2 \mu\text{F}$ (2×10^{-7}). How much current flows in the circuit at 10 Hz, 50 Hz, and 600 Hz?

TYPES OF CAPACITORS

In discussing dielectric constants earlier, we mentioned that a number of different materials can be used as a dielectric in a capacitor, and the dielectric constant of each material helps to determine the capacitance of a device of a given size. Capacitors are generally classified according to their dielectric material. Some of the more common types of capacitors will be discussed in this section.

Regardless of the type of capacitor, the schematic symbol is generally the same. The two most common schematic symbols for capacitors are shown in Fig. 4-7. Most capacitor types are interchangeable.

Ceramic Capacitors

Perhaps the most commonly used type of capacitor consists of a wafer of ceramic material between two silver plates. Leads are connected to the plates, and the entire assembly (except for the leads, of course) is encased in a protective plastic shield. See Figs. 4-8 and 4-9. This type is called a *ceramic capacitor*, or, because of its most common shape, a *ceramic disc*. Some ceramic capacitors, however, are enclosed in rectangular cases. There is no electrical difference, and often the rectangular units are called ceramic discs anyway.

The values for ceramic capacitors usually range from about 10 pF to about $0.05 \mu\text{F}$. Occasionally you'll also find ceramic capacitors with values up to $0.5 \mu\text{F}$.

There are two important voltage ratings for capacitors. One is the *breakdown voltage*. This is the absolute maximum voltage the dielectric material can withstand without breaking down and rupturing. For most dielectrics the breakdown voltage is quite high (typically, more than 10 kilovolts), so you generally don't have to worry about it in practical circuits.

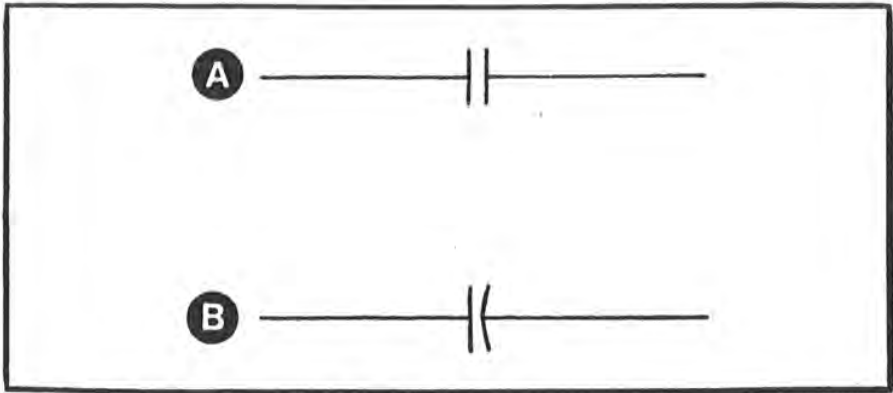


Fig. 4-7. Schematic symbols for capacitors.

The second important voltage rating in a capacitor is the *working voltage*. This is the maximum DC voltage the manufacturer recommends to be placed across the plates safely. Exceeding this voltage can damage or destroy the capacitor, and perhaps other nearby components. The working voltage is usually much lower than the breakdown voltage.

One thing that is important to remember is that the working voltage is given in DC volts. Since AC ratings are usually given in rms units, you must find the peak voltage to determine if it can safely be applied to a given capacitor. For example, if a capacitor has a working voltage rating of 100 volts, you should not apply an AC voltage of more than 100 volts peak. In terms of rms voltage this is 100×0.707 , or no more than 70.7 volts rms. If you put 100 volts rms across this device, the peak voltage would actually be 100×1.41 , or 141 volts. This much overvoltage could easily damage the capacitor.

Working voltages for standard ceramic capacitors generally range from 50 to about 1600 volts. If a lower voltage unit can do the job, it will generally be less expensive, but a higher voltage rating



Fig. 4-8. A ceramic disc capacitor.

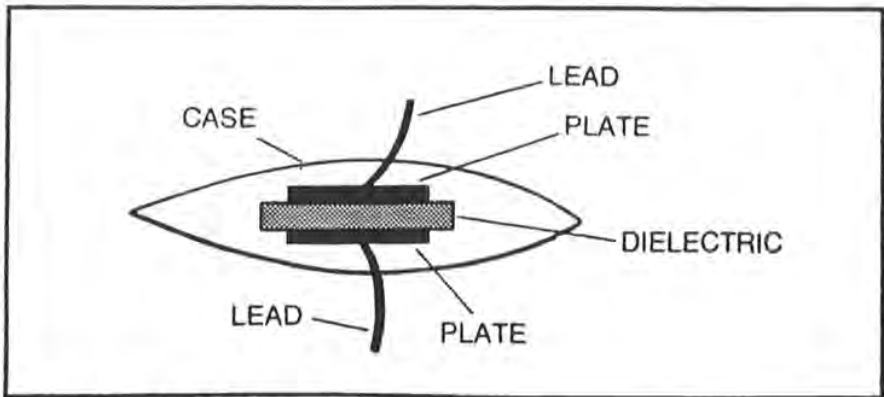


Fig. 4-9. Structure of a ceramic disc capacitor.

can always be substituted. Capacitors with low working voltages also tend to be physically smaller.

Special high capacitance ceramic capacitors are also available with capacitances up to about $0.5 \mu\text{F}$. Often this will be marked as $0.47 \mu\text{F}$ —capacitor values aren't precise enough for this small difference to matter. The working voltage for these large capacitance units is generally only about 10 to 100 volts.

The values are usually stamped right on the case of ceramic capacitors. This type of capacitor is very widely used because it is inexpensive, comparatively small, and has a low degree of power loss (leakage resistance). In radio frequency tuned circuits (very high frequencies) ceramic capacitors often prove to be unsatisfactory because of poor stability. But at frequencies up to about 100 kHz, they are generally an excellent choice.

Mica Capacitors

Another popular type of capacitor uses thin slices of mica sandwiched between a number of interconnected plates. See Figs. 4-10 and 4-11. Again, this type of capacitor is named after its dielectric. It is called a *mica capacitor*. As a rule, mica capacitors are somewhat more expensive than ceramic discs, but they tend to be much more stable at radio frequencies. Their values typically range from 5 pF to $0.01 \mu\text{F}$, and their working voltages are generally between 200 and 50,000 volts.

A special type of mica capacitor is the *silver-mica capacitor*. This is also sometimes called a *silvered mica capacitor*. In this type of capacitor a very thin coating of silver is applied directly onto the mica sheets, instead of the usual foil plates. These units are more expensive, naturally, but they can have capacitance tolerances as close as 1%. Most ordinary capacitors have a tolerance of only 10



Fig. 4-10. A mica capacitor.

to 20%. In most circuits a plus or minus error of 20% in the capacitance value really won't matter much, or can be compensated for by fine tuning a variable component. But in some special purpose circuits, precise values are needed, so silver-mica capacitors are used.

Sometimes a mica capacitor has its value stamped directly on its body, but other units are identified via a color code similar to the one used with resistors. Figure 4-12 shows the arrangement of color coding dots on a typical mica capacitor. Some indication, such as the arrow in the figure, will be given so that you will know which dot is which.

The first dot (dot A) is generally either white or black. This simply indicates that the unit is a mica capacitor. Dot B is the first significant figure of the capacitance value, and dot C is the second significant figure. The value for each color is shown in Table 4-2. Notice that the values for dot B and dot C are identical to the resistor color code.

The multiplier is given by dot F, directly below dot C—not dot D at the beginning of the next row, as might be expected. Dot F

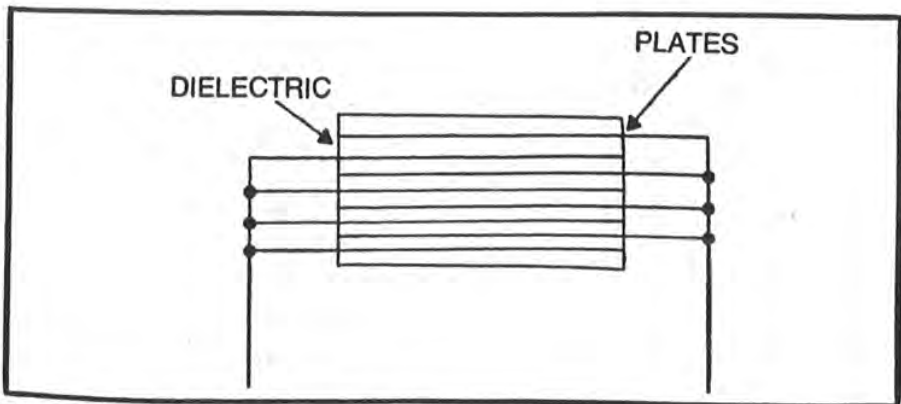


Fig. 4-11. Structure of a mica capacitor.

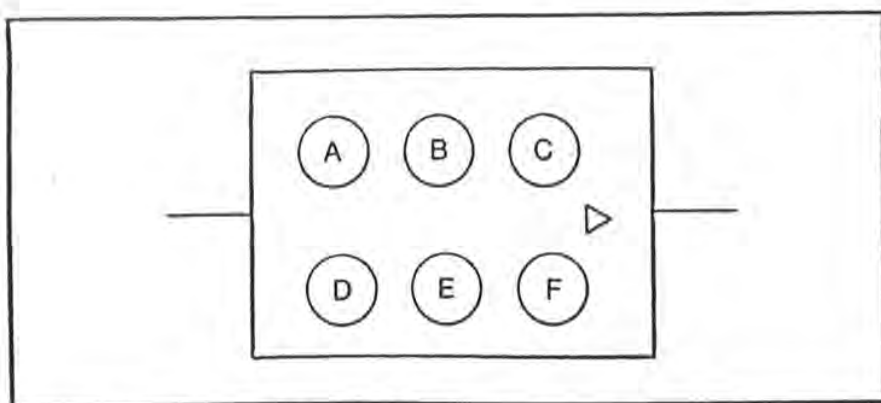


Fig. 4-12. Arrangement of color coding dots on a mica capacitor.

corresponds to the third band on a resistor. The color values are basically the same as in the resistor color code, but capacitors don't have as wide a value range as resistors, so some colors aren't used as multipliers. Multiplying the significant figures by the multiplier gives the capacitance value in picofarads (pF). To convert to microfarads (μF), you must divide the result by 1,000,000.

Dot D in the lower left hand corner gives the *temperature coefficient* for the capacitor. The capacitance will vary somewhat with changes in temperature. The temperature coefficient tells you the maximum extent of the fluctuation for a given change in temperature. It is given in parts per million per degree centigrade. For example, if dot D is red, the temperature coefficient is ± 200 . This means if the temperature changes one degree centigrade, the value may increase or decrease by no more than 200 parts per million, or 0.02%.

Notice that some capacitors can increase in value more than they decrease. In fact if dot D is green, the capacitance can only increase. The value marked is said to be the *minimum guaranteed value*.

Dot E simply gives the manufacturing tolerance of the capacitor. It corresponds to the fourth band on a resistor.

Let's suppose we have a capacitor with the following markings; Dot A is white, dot B is brown, dot C is black, dot D is orange, dot E is black, and dot F is brown. What is the value of this capacitor.

White at dot A simply indicates that this is a mica capacitor. Dot B is brown, which means the first significant figure is 1. Black at dot C means the second significant figure is 0. The value of the capacitor is 10 times the multiplier value. Dot D is orange so the capacitor has a temperature coefficient of plus or minus 100 parts

per million (0.01%). The tolerance is given by dot E, which is black. This guarantees the actual value is within plus or minus 20% of the value marked. Dot F is the multiplier. It is brown on our sample resistor, so the multiplier is 10. The value of this capacitor is 10×10 , or 100 pF plus or minus 20%, with a temperature coefficient of plus or minus 0.01%. Since the marked value has a tolerance of 20%, the actual value of the capacitor can range from 80 to 120 pF and still be correctly marked.

Let's assume the capacitance value is exactly as marked—100 pF, and the temperature changes 3 degrees centigrade. This will cause the value of the capacitor to change as much as 0.03 pF in either direction.

Now, let's suppose the temperature changes 50° centigrade. The value can change by plus or minus 0.5 pF. That is still not very much. You can see that the temperature coefficient can usually be ignored in practical circuits unless very wide fluctuations of temperature are expected. If dot A is black, it simply means the capacitor was manufactured to military specifications.

Paper Capacitors

Sometimes a higher capacitance is needed in a circuit than a ceramic disc or a mica capacitor can provide. Another type of

Table 4-2. The Capacitor Color Code.

Color	Dot A	Dot B	Dot C
Black	Mica	0	0
Brown	--	1	1
Red	--	2	2
Orange	--	3	3
Yellow	--	4	4
Green	--	5	5
Blue	--	6	6
Violet	--	7	7
Gray	--	8	8
White	Mica	9	9
Silver	Paper	--	--
Color	Dot D	Dot E	Dot F
Black	± 1000	$\pm 20\%$	X 1
Brown	± 500	$\pm 1\%$	X 10
Red	± 200	$\pm 2\%$	X 100
Orange	± 100	$\pm 3\%$	X 1000
Yellow	-20 to +100	--	X 10000
Green	0 to +70	$\pm 5\%$	--
Gold	--	$\pm 5\%$	X 0.1
Silver	--	$\pm 10\%$	X 0.01

capacitor can be formed by placing a strip of waxed paper (dielectric) between two long strips of tin foil (plates). These foil strips are often several feet long, but only about an inch wide. This assembly can be tightly rolled up to save space, and it is usually enclosed in a cardboard tube or plastic container. Such a device is called a paper capacitor or a tubular capacitor. See Figs. 4-13 and 4-14. Of course, leads are connected to the foil strips and brought out through the ends of the cardboard tube. In some units, the capacitor is sealed in a metal or plastic case to prevent moisture from getting into the capacitor.

The capacitance range for paper capacitors is from about $0.0001\ \mu\text{F}$ to about $1\ \mu\text{F}$, with working voltages from 200 to 5000 volts.

Paper capacitors are relatively inexpensive, but they have a fairly low leakage resistance (a paper capacitor has a lower leakage resistance than, say, a mica capacitor), and they have some trouble giving optimum performance at the upper radio frequencies because of high dielectric losses. However, they are an excellent choice when a fairly large amount of capacitance is needed in a low or medium frequency circuit, especially when space is at a premium.

Paper capacitors generally have their values stamped directly onto their bodies, but sometimes they are color coded with the same system used for mica capacitors. For a paper capacitor, dot A is always silver.

Synthetic Film Capacitors

A similar type of capacitor can be made using a thin coating of synthetic film instead of waxed paper as the dielectric. Such a capacitor is usually identified by the specific type of film it uses. For example, there are *polystyrene capacitors*, *Mylar capacitors*, and *polyester capacitors*.

These synthetic films are usually thinner than the paper used in paper capacitors, so a film capacitor of a given value will tend to be somewhat smaller than a paper capacitor of the same capacitance.

Another advantage of these film capacitors is that they can operate over a wider temperature range than the paper units. In other words, they have a lower temperature coefficient. They also tend to be somewhat more precise, and closer to the marked value. That is, the tolerance is smaller. The capacitance of synthetic film

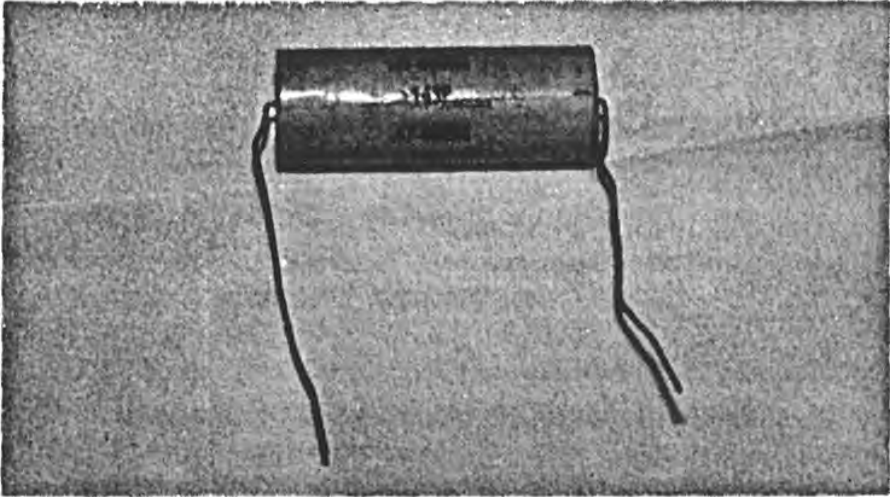


Fig. 4-13. A paper capacitor.

capacitors ranges from $0.001 \mu\text{F}$ to about $2 \mu\text{F}$. The working voltages are generally between 50 and 1000 volts.

Electrolytic Capacitors

The capacitors we have been talking about so far are *non-polarized*. That is, they can be placed in a circuit with the leads connected in either direction. Other capacitors are designed to work only in DC circuits and can only be hooked up one way. Such a component is said to be *polarized*.

The schematic symbol for a polarized capacitor is basically the same as for a regular capacitor, but a "+" is added at the positive terminal to indicate polarity. See Fig. 4-15. This terminal must be kept positive with respect to the other terminal.

The most common type of polarized capacitor is the electrolytic capacitor. This type of capacitor consists of a pasty, semi-liquid

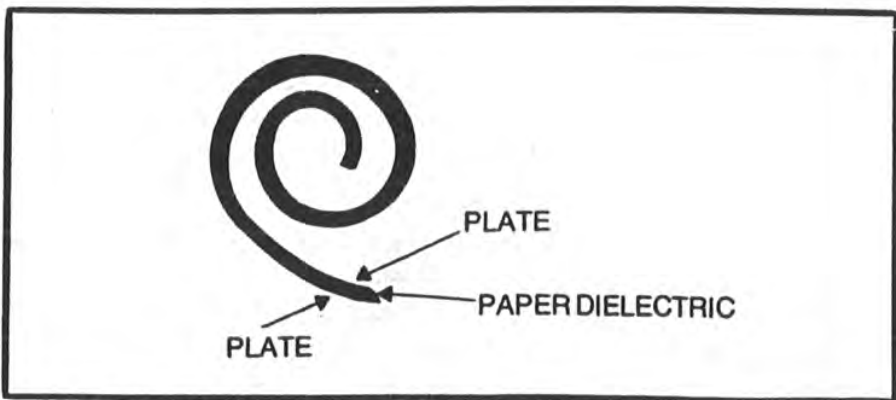


Fig. 4-14. Structure of a paper capacitor.

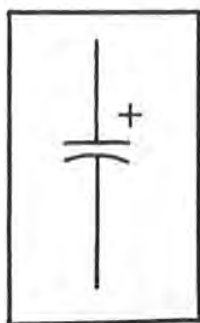


Fig. 4-15. Schematic symbol for a polarized capacitor.

electrolyte between aluminum foil electrodes, or plates. The positive plate is specially treated to form a thin oxide film on its surface. This film serves as the capacitor's dielectric. If the capacitor is subjected to a reverse polarity voltage, this thin layer of film could be punctured, ruining the capacitor.

Because the dielectric is such a thin film, very high capacitance values can be achieved in a reasonably small space. Typical values range from $0.47 \mu\text{F}$ to $10,000 \mu\text{F}$ (0.01 Farad), and occasionally even higher. Working voltage ratings can be anywhere from 3 to 700 volts. The leads on an electrolytic capacitor can be placed in either an *axial* (Fig. 4-16) or a *radial* (Fig. 4-17) arrangement.

Internally an electrolytic capacitor resembles the construction of a paper capacitor, except, of course, the dielectric is considerably thinner.

One problem with electrolytic capacitors is that the semi-liquid electrolyte can dry out, rendering the capacitor useless. This generally occurs when the capacitor is not in use—applying a voltage across it seems to prevent the electrolyte from drying out—so it is not a good idea to stock pile electrolytic capacitors in large quantities for possible future use.

Similarly, drying out can sometimes occur if the electrolytic capacitor is operated from too low a voltage. If the voltage is extremely low, then, as far as the capacitor is concerned, it is still just sitting on the shelf. Certainly a 15 volt capacitor could be used in a 5 volt circuit, but you wouldn't want to use a 500 volt unit. Besides, capacitors with higher working voltages are much larger, heavier, and more expensive than smaller units.

Preferably an electrolytic capacitor should be operated at a voltage between one third and two thirds of its rated maximum. This is enough to keep the electrolyte from drying out, but allows for unexpected over-voltage surges.

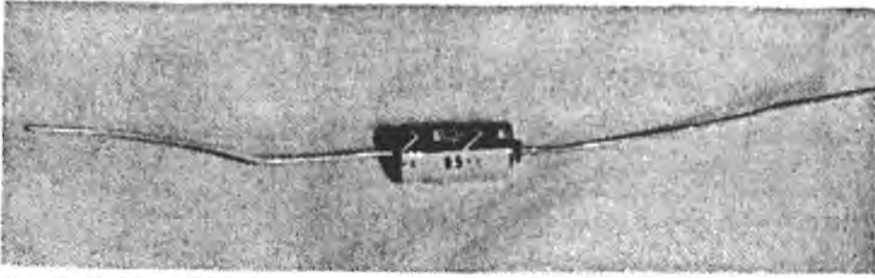


Fig. 4-16. An electrolytic capacitor with axial leads.

It might seem that the electrolytic capacitor would be of rather limited value because of its inability to function in an AC circuit, but actually it has a large number of important applications. These include power supply filtering, circuit coupling, audio frequency bypassing and achieving large time constants in RC circuits (described later in this chapter).

Electrolytic capacitors usually have a very wide tolerance. They might vary from their nominal value by as much as plus or minus 50 to 70%. Except in critical timing applications, the precise value is rarely important, so this loose tolerance is acceptable.

Tantalum Capacitors

Closely related to the electrolytic capacitor is the *tantalum capacitor* (see Fig. 4-18). Like the electrolytic capacitor, it can only be used in DC circuits. A dot on the body of the capacitor indicates the positive lead.

Tantalum capacitors offer a number of advantages over their electrolytic counterparts. They tend to be considerably smaller for a given capacitance value. They aren't as prone to drying out. They have less leakage. Their values tend to be more precise (lower tolerance) and they are much less susceptible to noise. Especially because of the last reason, they are generally preferred in computer applications. On the other hand, they tend to be more



Fig. 4-17. An electrolytic capacitor with radial leads.

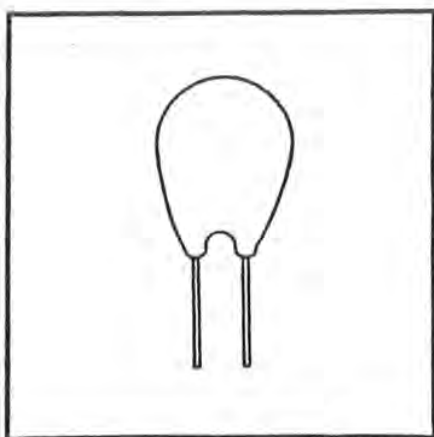


Fig. 4-18. A tantalum capacitor.

expensive than electrolytic capacitors, and they are limited to a much smaller range of capacitances and working voltages. Usually they range only from $0.5 \mu\text{F}$ to about $50 \mu\text{F}$ with working voltages that are rarely higher than 50 volts.

Variable Capacitors

Most capacitors have a single fixed value, but, just as there are variable resistors, there are *variable capacitors* too. One type uses a springy material for the plates. If they weren't held in place, the plates would fly apart. Between the plates is a piece of dielectric material, such as mica. The assembly is held together by a screw. By tightening or loosening this screw, the distance between the plates can be changed, thus altering the effective capacitance of the device. Figure 4-19 illustrates the structure of this type of capacitor. This kind of variable capacitor is called a *padder capacitor*, or a *trimmer capacitor*.

Another type of variable capacitor consists of a series of interweaved metal plates. One set (called the *stator*) is stationary. The other set of plates (called the *rotor*) can be moved by a knob. The amount of overlap between the plates determines their effective area. Moving the rotor electrically acts like the plates are being increased or decreased in area. Figure 4-20 illustrates the way this works. The dielectric in this type of capacitor is simply air. It is called a *variable air capacitor*. The schematic symbol for either type of variable capacitor is shown in Fig. 4-21.

RC TIME CONSTANTS

If a resistor and a capacitor are connected in series across a voltage, as in Fig. 4-22A, the capacitor will be charged through the

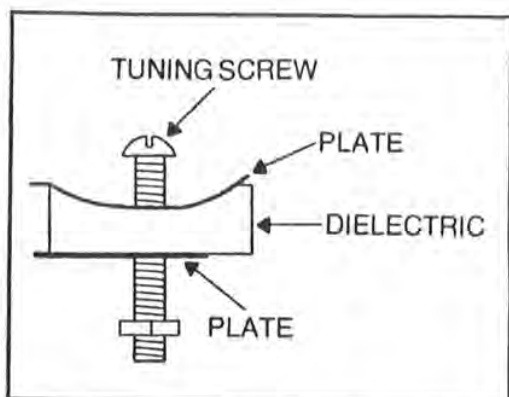


Fig. 4-19. A trimmer capacitor.

resistor at a specific rate, determined by both the capacitance and the resistance. The capacitance, of course, determines how many electrons the negative plate can hold when fully charged, and the resistance slows down the flow of electrons.

The time it takes for the capacitor to be charged to 63% of its full potential charge level is called the *time constant* of the combination. For obvious reasons, such a combination of a resistor and a capacitor is called an *RC circuit*.

Similarly, if the voltage source is removed, as in Fig. 4-22B, the capacitor will be discharged through the resistor. In this case, the time constant is defined as the time it takes the capacitor to drop down to 37% of its fully charged value. The charging time constant and the discharging time constant are always equal.

The time constant of a specific RC circuit can be found simply by multiplying the resistance and the capacitance;

$$T = RC \quad \text{Equation 4-3}$$

T is the time constant in seconds, R is the resistance in megohms (1 megohm = 1,000,000 ohms), and C is the capacitance in microfarads (μF).

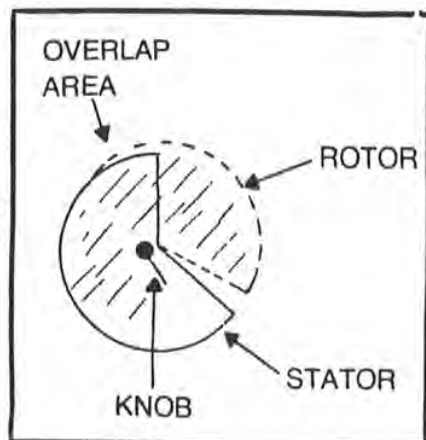


Fig. 4-20. A section of a variable air capacitor.

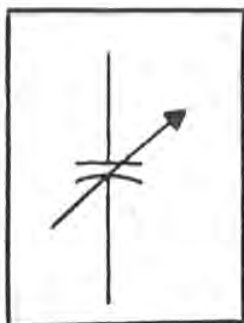


Fig. 4-21. Schematic symbol for a variable capacitor.

For example, if the resistor has a value of 100,000 ohms (0.1 megohm) and the capacitor is $10\ \mu\text{F}$, the time constant will be equal to $0.1\ \text{megohm} \times 10\ \mu\text{F}$, 1 second. The same time constant could be achieved with other RC combinations. For example, 1 megohm and $1\ \mu\text{F}$, or 10,000 ohms and $100\ \mu\text{F}$ would also result in a one second time constant.

As another example, let's take a 470,000 ohm (0.47 megohm) resistor and a $2.2\ \mu\text{F}$ capacitor. The time constant in this circuit would equal $0.47\ \text{megohm} \times 2.2\ \mu\text{F}$, or 1.034 second.

If the resistor is 22,000 ohms (0.022 megohm), and the capacitor is $0.3\ \mu\text{F}$, the time constant is 0.022×0.3 , or 0.0066 second (6.6 milliseconds).

Here are two more examples for you to work out on your own. What is the time constant for an RC circuit consisting of a 3.9 megohm resistor and a $0.68\ \mu\text{F}$ capacitor? How about a 910,000 ohm resistor and a $15\ \mu\text{F}$ capacitor?

FILTERS

A *filter* is a circuit that allows some frequencies to pass through it, while others are blocked. A capacitor is automatically a sort of filter by definition, since it allows higher frequencies to pass through it easily, while it blocks a DC signal (ie., 0 Hz). A filter that passes high frequencies, but blocks low frequencies is called a high-pass filter.

The circuit for a practical, but simple high-pass filter is shown in Fig. 4-23. High frequencies are passed with little or no *attenuation*. That is, they are not reduced in level. But, at some specific frequency, the filter starts to impede the passage of the signal. This is the *cut-off frequency*.

It would be impossible to design a practical filter that would completely block all signals below the cut-off frequency, and completely pass all frequencies above it. Instead, the level of the signal allowed to pass through the filter begins to drop off at a

regular rate. This dropping off is called the *slope* of the filter. Obviously, the steeper the slope, the better the filter. For a simple filter, such as the one in Fig. 4-23, the slope is quite broad. A graph of the filter's frequency response is shown in Fig. 4-24.

The formula for finding the cut-off frequency of this type of filter is,

$$F_c = \frac{158,000}{RC} \quad \text{Equation 4-4}$$

Resistance (R) is in megohms, and capacitance (C) is in microfarads, so the resulting cut-off frequency (F_c) is in Hertz.

Notice that the denominator in this equation is the formula for finding the time constant of an RC circuit. The formula could be rewritten as,

$$F_c = \frac{159,000}{T} \quad \text{Equation 4-5}$$

T is the time constant in seconds.

Let's try a few examples with equation 4-4. Let's suppose the

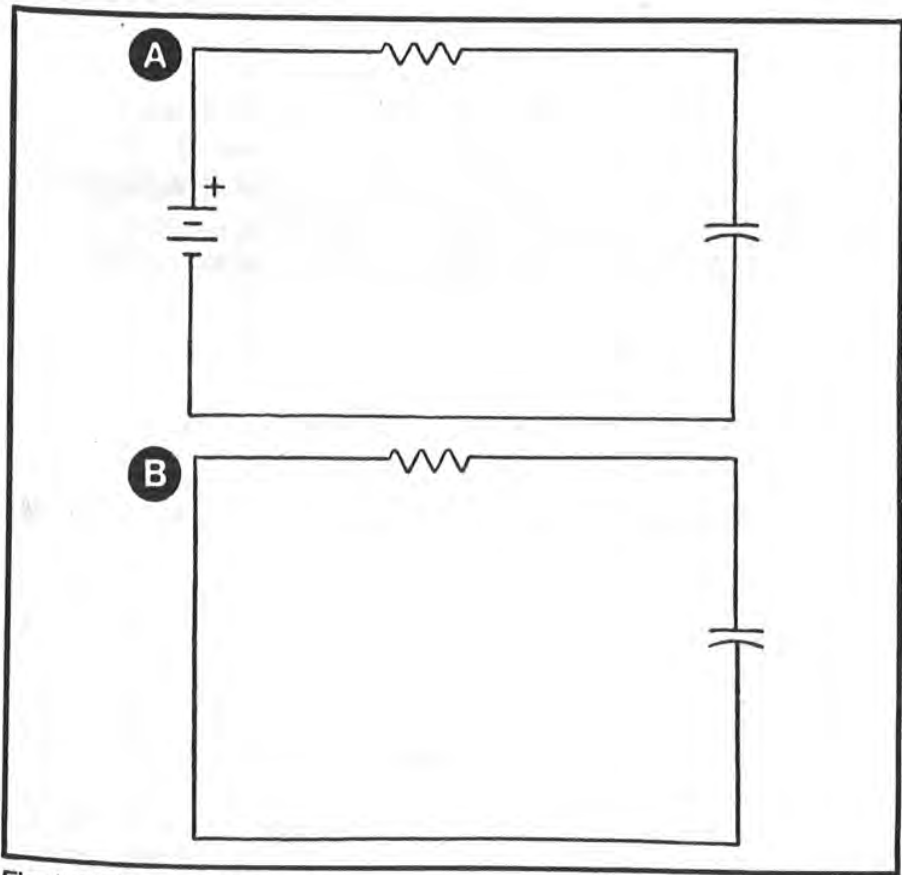


Fig. 4-22. A series RC circuit.

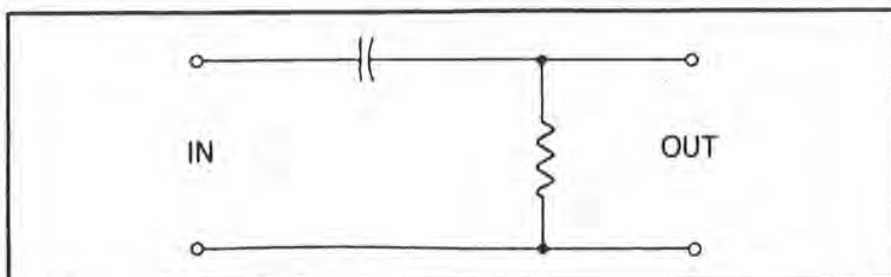


Fig. 4-23. A high pass filter.

circuit in Fig. 4-23 consists of a 3.3 megohm resistor (3,300,000 ohms) and a $0.68 \mu\text{F}$ capacitor. The cut-off frequency would equal $159,000/(3.3 \times 0.68) = 159,000/206.04$, or approximately 772 hertz.

If we replace the resistor with a 820,000 ohm (0.82 megohm) unit, and keep the same capacitor, the cut-off frequency now becomes $159,000/(0.82 \times 0.68) = 159,000/0.5576$, or approximately 285,000 Hz.

Now let's keep the 0.82 megohm resistor and use a $0.002 \mu\text{F}$ capacitor. $F_c = 159,000/(0.82 \times 0.002) = 159,000/0.00164 = 96951220 \text{ Hz}$, or just under 97 MHz.

Notice that if either the capacitance or the resistance is decreased in value, the time constant decreases, and the cut-off frequency increases. Of course, it also works in the other direction. Increasing either the resistance or the capacitance will increase the time constant and decrease the cut-off frequency.

Try finding the cut-off frequency for the following combinations.

R	C
470,000 ohms	$0.1 \mu\text{F}$
3.9 megohms	$22 \mu\text{F}$
22 kilohms	$150 \mu\text{F}$

Now, what would happen if we reversed the positions of the resistor and the capacitor, as shown in Fig. 4-25?

In this case the capacitor provides a *short-circuit*, or *shunt* across the signal source for high frequencies, but not for low frequencies and DC, which can't pass through the capacitor. Since current will tend to flow through the path with the least resistance (or reactance), very little high-frequency current will get through to the output.

Low frequencies, however, face a high reactance if they try to flow through the capacitor to ground, so they will appear at the output.

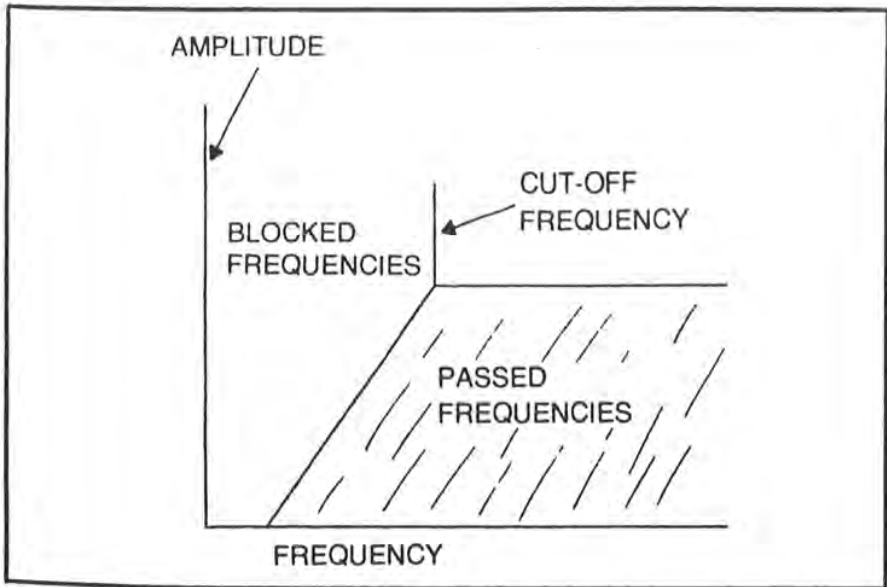


Fig. 4-24. A frequency response graph for a high pass filter.

This filter, then, passes low frequencies, but blocks high frequencies. Of course, this circuit is called a *low-pass filter*. It operates as an exact mirror image of the high-pass version, as is indicated by its frequency response graph (Fig. 4-26). The formula for finding the cut-off frequency is identical for both circuits.

COMBINATIONS OF CAPACITORS

Now, let's examine what happens when we have more than one capacitor in a circuit.

Capacitors In Parallel

A circuit with two capacitors in parallel, as shown in Fig. 4-27, can be drawn more pictorially, as in Fig. 4-28. Since plates A and B are tied together, they are at the same electrical potential. We can think of them as a single plate. Similarly, plates C and D are electrically combined into an apparent single plate.

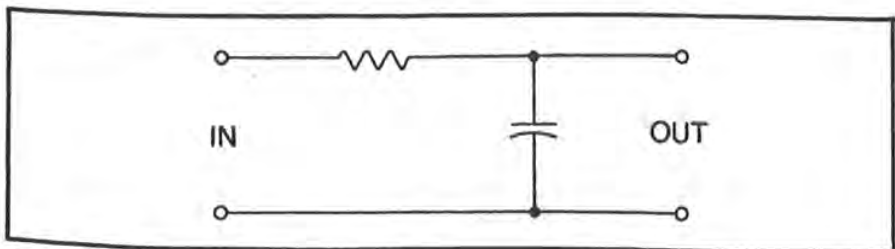


Fig. 4-25. A low pass filter.

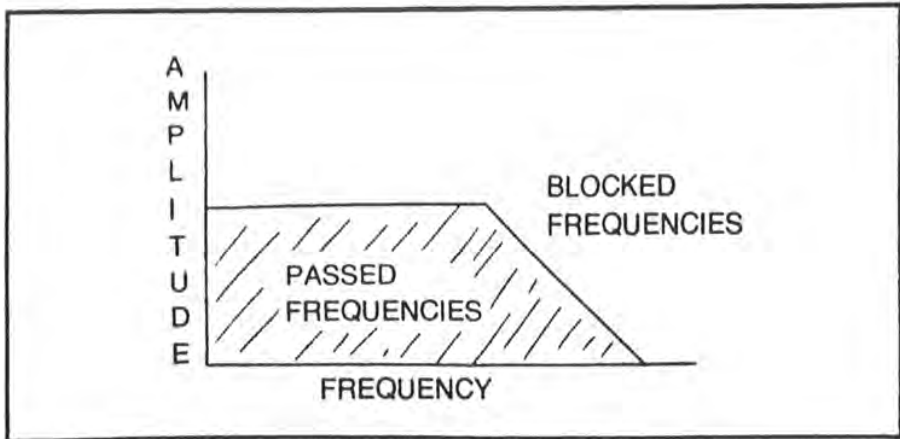


Fig. 4-26. A frequency response graph for a low pass filter.

Remember that the larger the surface area of the plates in a capacitor, the higher the capacitance will be. Obviously, combination plate A-B is going to be larger than either plate A or Plate B separately. The same is true of combination plate C-D. So the total effective capacitance of multiple capacitors in parallel always increases. The total capacitance is larger than any of the separate, component capacitances.

In fact, we can simply add the capacitances of capacitors in parallel. That is, for n capacitors in parallel:

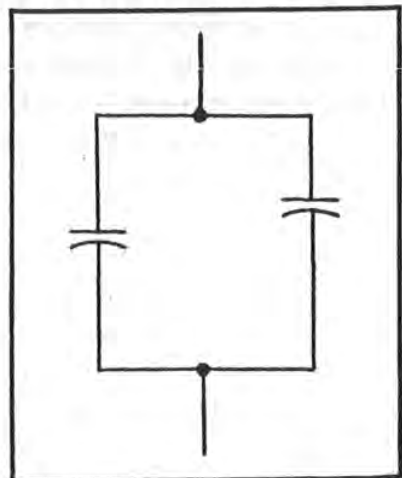
$$C_T = C_1 + C_2 + \dots + C_n \quad \text{Equation 4-6}$$

Notice that this is the same as the formula for finding the total resistance of multiple resistors in series.

Capacitors In Series

Similarly, capacitors connected in series, as in Fig. 4-29, work against each other, reducing the total effective capacitance of

Fig. 4-27. Parallel capacitors.



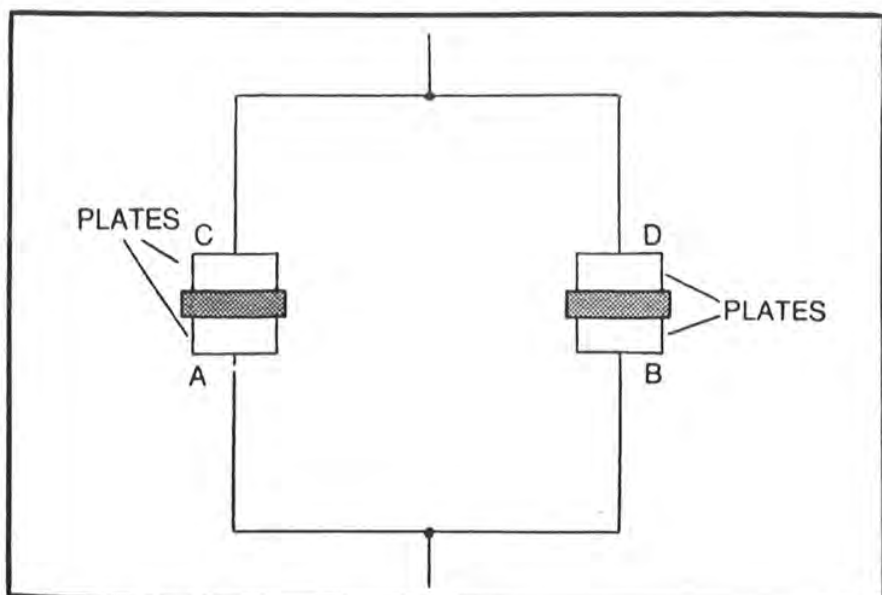


Fig. 4-28. Pictorial diagram of parallel capacitors.

the circuit. The formula for capacitors in series mirrors the formula for multiple resistors in parallel;

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n} \quad \text{Equation 4-7}$$

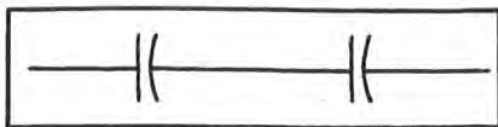
Therefore, two $0.1 \mu\text{F}$ capacitors in series would act like a single $0.05 \mu\text{F}$ capacitor. If the same capacitors were connected in parallel they would equal $0.2 \mu\text{F}$.

Of course, both series and parallel combinations of capacitances can be included within a single circuit, just as with resistances.

For example, consider the string of capacitors in Fig. 4-30. We'll assume C_1 is $0.1 \mu\text{F}$, C_2 is $0.033 \mu\text{F}$, C_3 is $0.0015 \mu\text{F}$, and C_4 is $0.22 \mu\text{F}$. First solve for the series combination of C_1 and C_2 . $1/C_T = 1/C_1 + 1/C_2 = 1/0.1 + 1/0.033 = 10 + 30.30303 = \text{about } 40$. Taking the reciprocal, we find the series combination of C_1 and C_2 is approximately $0.025 \mu\text{F}$. This capacitance is in parallel with C_3 , so $C_T = 0.025 + 0.0015 = 0.0265$.

This effective capacitance is in series with C_4 , so the effective capacitance for the entire circuit equals $1/0.0265 + 1/0.22 = 37.7$

Fig. 4-29. Capacitors in series.



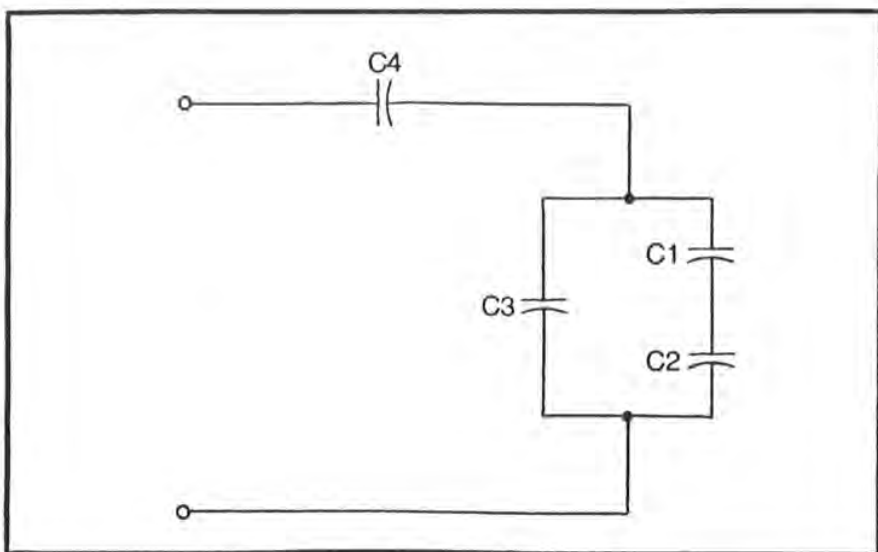


Fig. 4-30. A series/parallel capacitor circuit.

+ 4.5 = 42.2—taking the reciprocal we conclude that the total effective capacitance is just under $0.024 \mu\text{F}$.

Now, find the total effective capacitance for the circuit if $C1 = 15 \mu\text{F}$, $C2 = 0.47 \mu\text{F}$, $C3 = 3.3 \mu\text{F}$, and $C4 = 2.2 \mu\text{F}$.

STRAY CAPACITANCES

Since a capacitor is simply two conducting surfaces, separated by an insulator, small, unintentional capacitances can be formed by adjacent wires, or component leads. Generally these *stray capacitances* are far too small to be of any real significance, but in some very high frequency circuits (such as radio circuits) they can be very troublesome. These undesirable capacitances can allow signals to pass into portions of the circuit where they could hinder proper operation.

To prevent such stray capacitances in high frequency circuits, leads should be as short as possible reducing the effective plate area. Leads should also be *shielded* (ie., enclosed in a conductor that is connected to ground—either earth ground or common ground) if more than just a few inches long.