Inside Basic Electronics

By Sol D. Prensky

CAPACITORS AND RC CIRCUITS

CAPACITORS are so important in the realm of electronics that you'd be hard pressed to find a circuit that doesn't employ at least one of them. Often, the capacitor is teamed with a resistor. This *RC* combination plays a dominant role in shaping the network's overall *frequency response*. For a clear understanding of *RC* circuits, we'll first take a close look at the capacitor, and then see how it behaves when paired with a resistor.

Fundamentals of Capacitors. Every capacitor consists of two conductive plates separated by an insulating medium called a *dielectric* (Fig. 1). When a dc voltage is applied across the capacitor (by closing the switch), electrons start flowing from the negative terminal of the battery onto the bottom plate of the capacitor. Simultaneously, the battery's positive terminal attracts electrons from the top plate. At first, the electrons flow fairly easily. But as more and more of them are piled up on the bottom plate, it becomes increasingly harder for any more electrons to join them.

Here's why. Electrons are all negatively charged, and like charges tend to repel each other. Eventually this repulsive force will counteract the force generated by the battery which causes electrons to move, and no more current will flow. (When we talk of "current," we refer to *conventional* current, which flows in the opposite direction to the motion of electrons.) The voltage across the capacitor will equal that across the battery. Furthermore, the bottom plate will have a surplus of electrons and will be negatively charged. The top plate will have a deficiency of electrons and will be positively charged.

We can find out just how much charge the capacitor is holding by using the simple equation $Q = CV$. This means that the charge in *coulombs* (one coulomb =6.281 billion billion electrons!) is equal to the applied voltage times the capacitance in *farads*. (The farad, which is the basic unit of capacitance, is so named to honor the British scientist Michael Faraday.) Thus we see that the capacitance of a capacitor is a measure of how much charge it can hold. And this presents the key to understanding the capacitor—it is an *energy storing* device. If we open the switch in Fig. 1, the voltage across the capacitor remains the same. No current will flow through the dielectric to *discharge* the capacitor if the dielectric is a good insulator. So, the charges are trapped on the metal plates. We could attach a light bulb (or any other load) across the capacitor and it would behave like a battery until enough current flowed from one plate to the other to compensate for the charge unbalance. At that point, the voltage across the capacitor would be zero, because its charge would have been depleted.

Among the factors that determine capacitance are the area of each plate, the spacing between the plates, and a quantity called the *dielectric constant*. If the plates are made larger (increased area), the capacitance will rise. When the plates are moved further apart, capacitance decreases. If an insulating medium with a dielectric constant of 1 (air) is replaced with one having a constant of 2 (paper), capacitance will be doubled.

In electronic applications, the farad is much too large a unit of capacitance. The more common units are microfarads (µF or 10^{-6} F) and picofarads (pF or 10^{-12} F). Another quantity of interest is the *leakage resistance*. We noted before that a charged capacitor will hold its stored charge until a load is placed across it. But that represents an idealized situation. No dielectric is a perfect insulator, but can be represented as a resistor in parallel with the capacitor. This leakage resistance allows a leakage current to flow through it which tends to discharge the capacitor. In most cases, we want this resistance to be as high as possible—on the order of many megohms—to make the capacitor a good storage place of electric charge.

DC and AC Behavior. If we apply a dc voltage across a capacitor, we note a transient charging current which stops as soon as the capacitor has fully charged. In other words, once the capacitor has charged, it acts like an open circuit for dc signals, and will block them. But the capacitor behaves differently in ac circuits. Without getting into details, suffice it to say that a capacitor displays *reactance*, which is an opposition to the flow of ac. Although reactance is measured in ohms, it is not a true resistance. A reactance does not consume any power by converting it into heat, as a resistance does, but rather returns power to the source of the ac signal. Capacitive reactance varies inversely with frequency and capacitance. That is, when capacitance is increased, reactance decreases, and if frequency is increased, the reactance grows smaller. The formula for capacitive reactance is $X_C = 1/(2\pi fC)$, where X_C is measured in ohms, *f* in hertz, and *C* in farads. Using this formula, we find that a 1-µF capacitor has 160 ohms of reactance at 1000 Hz, and 16 ohms at 10,000 Hz.

One example of capacitive behavior is in blocking and coupling, which is one of the most common ways in which a capacitor is used. Tubes and transistors can amplify ac signals, but to work properly, certain dc voltages must be applied to them. The plate of a tube can be set at a dc level of several hundred volts in a high-power

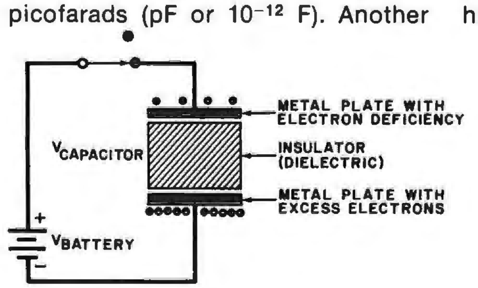

Fig. 1. The capacitor is basically a charge storing device.

amplifier. But we must take the ac output at this point without disturbing the dc level. So, we install a coupling capacitor at the plate. It acts as an open circuit to dc, but allows the ac signal to pass through it.

Of course, the capacitor must be chosen so that its reactance is low for the signal frequency, and its leakage resistance is high enough not to disturb the dc operation of the tube, as well as to prevent appreciable dc from flowing into the next stage or the load. Finally, we must choose a capacitor that can withstand the highest dc voltage that would exist across it. That is, it must have a sufficient *working voltage* rating. If this voltage is exceeded, the dc can arc over—as it does in a spark plug—with disastrous consequences.

Capacitor Types. Now that we know how a capacitor basically works, let's take a look at the various packages they are put in, and what materials are used to make them.

There are two major classes of capacitors: *polarized* (electrolytic) and *nonpolarized* types. The main factor that determines in which class or sub-class a capacitor falls is the dielectric material used. Nonpolarized capacitors can be inserted into a circuit without regard for which plate is positively charged, or which is negatively charged. Polarized capacitors are marked with one plate positive and the other negative. They must be inserted so that the positive plate is always at a higher potential (referenced to ground) than the negative plate.

Without delving too deeply into the peculiarities of each type, we can summarize the characteristics of nonpolarized capacitors as follows:

• *Paper dielectric* capacitors are the least expensive type to make. They cannot be used at frequencies much above 1 MHz, and are found primarily in audio circuits.

• *Organic film* types, such as polyester, Mylar, polystyrene, and polycarbonate capacitors, are intermediate in cost, offer large leakage resistance (10^{10} to 10^{14} ohms), and greater capacitance per unit volume than paper components. These dielectrics can also be used at higher frequencies than paper capacitors.

• *Ceramic dielectric* capacitors are widely used because they are fairly inexpensive, can be used in audio as well as r-f circuits (up to tens of MHz), and are available in capacitances from 1 pF to 1 μF, with working voltages up to several thousand volts. Leakage resistance is high, and they are marked for specific temperature coefficient information from *P* (positive, meaning increased temperature raises capacitance), to *N* for negative, in parts per million per degrees centigrade (ppm/°C). The designation *NPO* means negative-positive zero coefficient (virtually no change in capacitance over the −25° C to +85°C range).

•*Mica* or *silver mica* types offer excellent response into the vhf region, high leakage resistance, and tight tolerance (as low as ±1%, as opposed to ±10% or ±20% for other nonpolar capacitors). Working voltages can be made very high—on the order of several kilovolts. They are more expensive than ceramic capacitors, but are often used in precision and r-f applications, where increased cost is justified by superior performance.

• *Glass* is a dielectric that is superior to mica in many ways. *Glass capacitors* can be made to very close tolerances, and have excellent fre-

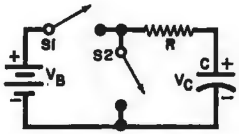

Fig. 2. Simple RC circuit.

quency response and leakage characteristics. They are also rather expensive.

The major limitation of all these nonpolarized capacitors is the amount of capacitance that can be packed into a container of reasonable volume. Up to about a tenth of a microfarad or so, packages are fairly small. But they become unwieldy as 1 μF is approached. For really large capacitances in small cans, we must use polarized or *electrolytic* capacitors.

These devices consist of two metallic electrodes separated by an *electrolyte* (hence their name). When a voltage is impressed across the electrodes, a thin film of nonconducting oxide is produced by chemical (electrolytic) action to form the dielectric. The rest of the electrolyte conducts fairly well, so the two electrodes are effectively separated only by the thin oxide layer. As we noted earlier, closely spaced plates mean high capacitance, and this is why the electrolytic capacitor has such high capacitance ratings. However, extreme care must be taken to insure that the proper polarizing voltage is applied, because reverse or excessive forward voltages can irreparably damage the capacitor.

The two most common types of electrolytic capacitors are *aluminum* and *tantalum*. They consist of either a foil (aluminum or tantalum) or a dry slug (tantalum). Foil units contain a liquid or gel electrolyte between the foil anode and the case that is in continuous contact with the oxide layer, and that participates in its formation. Slug-type capacitors employ a solid semiconducting electrolyte, and the anode is a sponge-like porous metal slug. In dry tantalum capacitors, manganese dioxide is commonly used as the electrolyte.

Dc leakage is an important factor in electrolytic capacitors. Some of them are quite leaky. Although this is tolerable in certain applications, it is most undesirable in others.

Tantalum capacitors generally display less leakage than aluminum components, and are often used because of this. Also, tantalums can be made to ±20% or even ±10% tolerances. Aluminum capacitors often have a +100%, −50% tolerance, which can rule out their use in certain circuits. Finally, aluminum electrolytics are frequency limited. They are useful up to 50 kHz at most, so are found mainly as filters in power supplies and as coupling or bypass capacitors (passing ac signals to the next stage or shunting them to ground) in audio circuits.

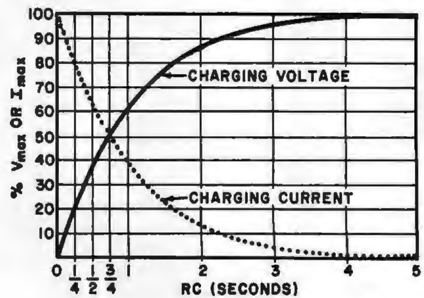

Fig. 3. Universal curves of charging voltage and current versus time.

Computer-grade electrolytics are found in power supplies because they can store large amounts of energy. You can find aluminum and computer grade capacitors rated at up to 10,000 µF or more and several hundred working volts, but today the high-voltage components are getting rare because solid-state circuits don't require the dc voltage levels that tubes do. Tantalum capacitors have ratings of a fraction of a microfarad up to 700 µF or so. Their voltage ratings generally lie between 3 and 50 volts.

Variable Capacitors. So far we have talked only about fixed capacitors. That is, those capacitors whose capacitance is set in the manufacturing. process. But *variable* capacitors are also very important. Every tuning-dial radio has at least one. The most common type of variable capacitor uses air as the dielectric, and has two sets of interleaved

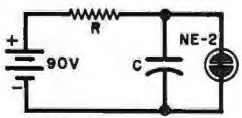

Fig. 4. Basic relaxation oscillator.

plates. One set, called the stator, is bolted to the frame of the capacitor. The other set, the rotor, is attached to a shaft that allows the two sets to be meshed (maximum capacitance), or

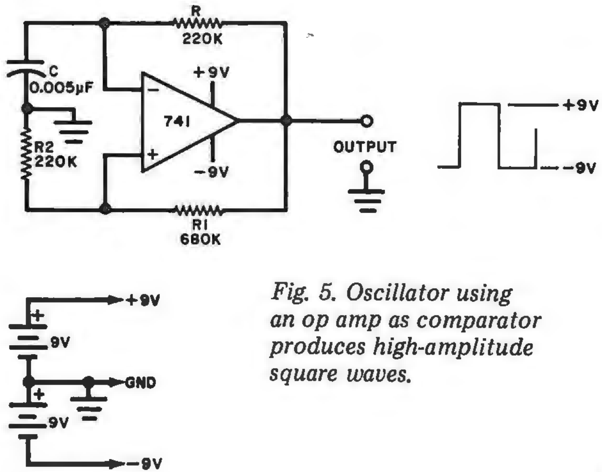

Fig. 5. Oscillator using an op amp as comparator produces high-amplitude square waves.

fully unmeshed (minimum capacitance), or anything in between. The capacitor is described by these two values, as well as its air gap (spacing between plates) and maximum working voltage. The latter two specifications are important in transmitting applications, where high-voltage r-f is present. In fact, sealed vacuum capacitors are available for high-power operation.

Other types of variable capacitors are *trimmers* and *padders*. They are used to fine-tune a network, and usually have screwdriver adjustments. They can have air, mica, plastic, or quartz dielectrics, and can take the appearance of a small pistion and cylinder, a small box, or two plates (one above the other) on a ceramic body.

All variable capacitors are noted for their small capacitance values. The typical tuning capacitor in an AM radio is rated at 365 pF maximum. Trimmer and subminiature tuning capacitors can have *maximum* capacitances of less than 10 pF! Remember, though, that capacitance isn't everything, and variable capacitors are indispensible in most communications equipment.

Combining R and C. When a resistor and capacitor are connected together, several interesting things happen. First, the relative magnitudes of *R* and *C* affect how quickly the capacitor will charge up. Second, the combination can act as a filter, passing high or low frequencies, depending on how the *RC* pair is connected across a signal source. Let's look at the dc charging action first.

The product of *R* in ohms and *C* in farads is called the *RC* time constant, and is symbolized by the greek letter tau (τ) and expressed in seconds or microseconds (μs). The time constant appears in many descriptions of the frequency response of oscillator and filter circuits, and is also important to the action of many pulse circuits. It is most easily understood as the factor that determines how fast a capacitor can charge through an effective resistance. From here we can determine the time *T* or period required for one complete cycle of oscillation, and thus the frequency.

If we were to close switch *S1* of the circuit in Fig. 2, and monitor the voltage across the capacitor with a voltmeter or oscilloscope, we would see that the voltage starts to build up rather quickly, but then the rate of increase drops off. Graphing the voltage against time or taking a snapshot of the scope trace would yield the solid-line curve shown in Fig. 3. It is an exponential curve that is universal in terms of the RC time constant.

We call the curve an exponential one because we can express the voltage across the capacitor by the equation $V_C = V_B\ (1 - e^{-t/\tau})$, where V_C is the voltage across the capacitor, V_B is the battery voltage, *t* is the time in seconds after the switch is closed, *e* is the base of natural logarithms (approximately 2.718), and τ is the time constant in seconds. The equation tells us that at t = zero seconds (as the switch is closed), the voltage across the capacitor is zero. After the number of seconds equal to one time constant, $V_C = V_B\ (1 - e^{-1})$, or $V_C = V_B\ (1 - 1/2.718)$. Solving this equation, we get $V_C = 0.63\ V_B$, or, after one time constant, the voltage across the capacitor has reached 63% of the battery voltage.

After one time constant, the capacitor charges more slowly. We can see from the graph that after two time constants the capacitor voltage is about 86% of the battery voltage, increasing to about 98% after four time constants. Theoretically, it would take the capacitor an infinite amount of time to charge to the full battery voltage; but, as a practical matter, we will consider the capacitor to be fully charged after 5 time constants have passed. Unlike voltage, charging *current* decreases with time. It is shown as the dotted curve in Fig. 3, and essentially is a mirror image of the voltage curve. We can see that charging current never stops (it would take an infinite time to do so), but after 5 time constants it is less that 1% of its initial turn-on value.

In the theoretical case shown in Fig. 1, the capacitor will hold its charge forever after it is disconnected from the voltage source, if its leakage resistance is infinite. Although this is never the case in practical components, good capacitors will hold most of their charge for a reasonably long time. (That's why it's dangerous to handle line powered electronic equipment *after power has been removed* if you haven't discharged the filter capacitors with a shorting stick.) But what happens if we allow capacitor *C* to discharge through *R*? We can do this by opening *S1* in Fig. 2 and then closing S2—which has been open up to this point.

If we use our oscilloscope or voltmeter to monitor the voltage across the capacitor, we'll see that it decreases exactly the same way as the charging current did. That is, after one time constant the voltage will have decreased to 37% of its open circuit value. As more time passes, the capacitor discharges more slowly. After two time constants, voltage is down to 14%; after three time constants it's at 5%; after four, 2%; and after five, slightly less than 1%. Although a theoretical, ideal capacitor will never fully discharge, we can say practically that it has done so after five time constants have elapsed.

RC Relaxation Oscillators. One circuit that is directly governed by the *RC* time constant is the *relaxation oscillator*. It depends on the alternate charging and discharging of a capacitor through a resistance. Probably the simplest relaxation oscillator you can build is a neon lamp flasher, shown in Fig. 4. The circuit is similar to that of Fig. 2, but we have added a neon bulb in parallel with the capacitor. Until a certain voltage threshhold is reached, the bulb acts like a very high resistance, practically an open circuit. Once the threshold is exceeded, the bulb turns on (conducts current and glows). In its on state, the bulb acts like a low resistance and will conduct very heavily unless a series current-limiting resistor is used with it. For common neon bulbs, the turn-on threshold is about 70 volts.

When the battery is connected, the capacitor starts charging up at a rate dependent on the time constant. After about 1.3 *RC* seconds have passed, the bulb suddenly turns on and discharges the capacitor very quickly. When the capacitor is discharged, no more current can flow through the bulb so it turns off. Then the capacitor begins to charge again. Oscillations, which we perceive as the flashing of the neon lamp, will continue as long as sufficient voltage is applied across the *RC* combination. You can duplicate this circuit very easily. Use an NE-2 neon bulb, a 90-volt photoflash battery, a small capacitor (0.1 µF or less at 250 WVDC), and a large resistance (over two megohms). You can vary the flashing rate by changing *R* or *C*, or both. Just stay within the guidelines suggested above.

A more up-to-date relaxation oscillator is shown in Fig. 5. It uses the 741 op amp as a comparator, and produces high-amplitude square waves. Here's how it works. Assume a positive output voltage appears when we initially apply power. This charges *C* through *R* to a positive voltage. Charging proceeds until the voltage across the capacitor exceeds that applied to the noninverting (+) input by the voltage divider *R1R2*. At this point the comparator produces a large negative output voltage, which discharges the capacitor through *R* and starts to charge it to a negative voltage. When the voltage across the capacitor exceeds that at the (+) input of the op amp, the output voltage goes positive, and the process repeats itself.

The *RC* time constant controls the duration of the high (t_1) and low (t_2) output durations. The presence of the voltage divider and the value of the power supply voltage also play a role. For the values given in Fig. 5, the period T for a complete oscillation equals the sum of t_1 and t_2, or $T = 0.9$ RC, and the frequency $f = 1/\tau = 1/990 \times 10^6$, or approximately 1000 Hz. If we increase *C* to 5 µF, we get about one pulse per second. ◈