

Understanding Basic Analog - Passive Devices

Application Report

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ABSTRACT

This application report describes passive devices such as resistors, capacitors, and inductors that are required to build an electronic circuit along with active devices. A well-designed circuit consists of passive devices selected to obtain specified performance.

Introduction

Passive devices are the resistors, capacitors, and inductors required to build electronic hardware. They always have a gain less than one, thus they can not oscillate or amplify a signal. A combination of passive components can multiply a signal by values less than one, they can shift the phase of a signal, they can reject a signal because it is not made up of the correct frequencies, they can control complex circuits, but they can not multiply by more than one because they lack gain.

All the glory goes to the sophisticated high gain amplifiers, but they are useless without the resistors and capacitors which control their gain. Good circuit design practice demands accurate and stable amplifiers, but active devices are by nature unstable, so they are tamed with passive components. Feedback is employed in almost all circuit designs to insure that the circuit performance is a function of the passive rather than the active components.

Passive devices are neglected in the rush to complete the design of an electronic system. Many engineers select passive devices as an afterthought; they just pick them from a list of standard components. Although this practice is adequate for some circuits, it does not suffice in the demanding world of high-frequency amplifiers, precision sample-holds, data converters, or other demanding circuits. The hardware designer must select adequate passive components to obtain specified performance in demanding applications.

The selection criteria for passive devices is as demanding as the applications for which they are used. The first selection criterion for passive components dictates that they be accurate and stable to insure proper circuit performance. After this criterion is satisfied, there are further requirements for low cost, small size, and surface-mounting, which must be met to satisfy the design specifications. Accuracy normally dictates larger size, so the accuracy requirement and the small size requirements often conflict. New surface-mount components are being introduced each day; thus, the design engineer is in a constant search to find accurate and stable passive components which meet all the criteria.

Detailed specifications including definitions of parasitic components are available from the various component manufacturers. Usually a call, letter, or email to one of these manufacturers requesting application information results in a flood of responses. The applications information should contain detail about the components, equations, dimensions, and graphs of salient parameters, photographs, tolerances, mechanical dimensions, and reliability data. If a component manufacturer cannot or will not send you this information, switch to a different manufacturer.

Resistors

There are many different resistors available for use, but only a few of them are satisfactory for accurate, stable, or high-frequency circuits. The first group of resistors includes the wirewound and composite power resistors; these resistors have too much stray inductance and capacitance to be usable at high frequencies. Because these resistors are made of wire which changes value when the temperature rises (either from self-generated heat or an external heat source), they have very poor temperature drift coefficients.

Most carbon film resistors have less stray capacitance and inductance, so they are usable at higher frequencies, but they are limited to about one percent accuracy. In addition, carbon film resistors tend to drift with temperature and vibration. Carbon composition resistors have lost their popularity to carbon film resistors because of the cost difference, but they are still used in many applications. It is reasonable to assume that a carbon composition resistor will act much like a carbon film resistor.

Metal film resistors share the stray inductance and capacitance problem with carbon films, but to a lesser extent. Metal film resistors come in smaller initial tolerances approaching 0.5%, and they are more stable under temperature and vibration extremes. Tolerances of 0.1% and lower are hard to achieve, but there are specialty houses which make precision resistors with tolerances below 0.1% on a daily basis.

Film resistors have pretty good noise performance, but some of the old carbon composition types had outstanding noise performance. When noise performance is a critical specification in a design, the resistor selection becomes very complicated. The problems associated with leaded resistors are complicated when working with surface mount resistors because of their small size. Some very good surface-mount resistors have come on the market lately, but the surface-mount selection still leaves a lot to be desired.

Inexperienced engineers assume that a resistor is just a resistor, but it is a very complicated circuit as Figure 1 illustrates. L_L simulates the inductance of each lead. C_P is the capacitance across the resistor; thus, it appears to be in parallel with the resistor. C_P is about 0.5 pF for a 250 mW resistor.

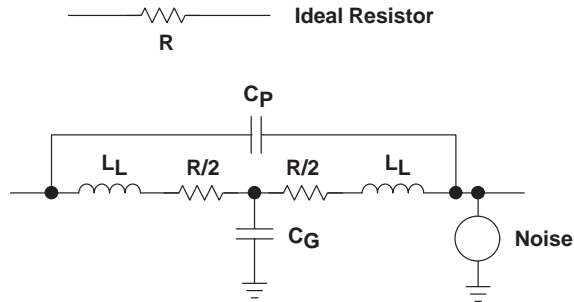


Figure 1. Resistor Equivalent Circuit

C_G is a capacitance formed by the resistor body and the ground plane, and it, like the rest of these stray effects, is a distributed effect. It can be modeled as a capacitor connected to ground from the center of the resistor because its value is small. Depending on the physical size of the resistor, C_P ranges from 0.01 pF on up to 0.5 pF. The stray effects are reduced as the size of the resistor is reduced. Surface-mount resistors have the best high frequency performance primarily because of their small size. The equation for a resistor when it is used in a circuit is given in equation 1, where V is the voltage across the resistor, and I is the current flowing through the resistor.

$$R = \frac{V}{I} \tag{1}$$

Variable Resistors or Potentiometers

Potentiometers (often called pots) are used to adjust the voltage or current at some point in a circuit. When tolerances stack up or when the specifications for a component can not be predicted accurately, pots are used to adjust out the tolerances. This adjustment enables the designer to obtain the correct circuit parameter regardless of tolerances. The overuse of potentiometers is often a sign of poor design because there are sophisticated methods for compensating for drift and tolerances. Some equipment such as projection displays use many adjustments to correct for mechanical deficiencies in the display system and these adjustments can not be designed out.

Pots have all the problems associated with fixed resistors, and they exacerbate some of them while introducing new ones. Pots are notorious for drifting under temperature, vibration, or other forms of stress. The connection from the resistive element to the lead is critical in fixed resistor design, and resistor manufacturers have become so good at making the connection that it is not considered a problem. The wiper on a pot must slide across the resistive element; thus, a good firm connection is impossible leading to a relatively high resistance connection. The best pots use films for the resistor elements, thus the wiper slides across a film where it is easier to make a low resistance connection. Beware, there is a maximum current allowed through the wiper, and either the circuit design or an external fixed resistor must be used to limit the wiper current to a safe value.

Systems that use large numbers of pots are converting to digital to analog (DAC) converters. DACs come eight and twelve to a package, and their cost is becoming equivalent to that of a pot. The adjustments are made through the keyboard or through a production test fixture. Smart systems self calibrate on start-up thus eliminating the need for pots.

Pots are used in two major applications: as voltage dividers for setting a reference voltage and as variable resistors, and both of these applications are shown in Figure 2. The voltage divider application uses the pot to set a reference voltage. The circuit shown in Figure 2 is a popular voltage divider application, and when the load resistance is much greater than the pot resistance, equation 3 represents the transfer function.

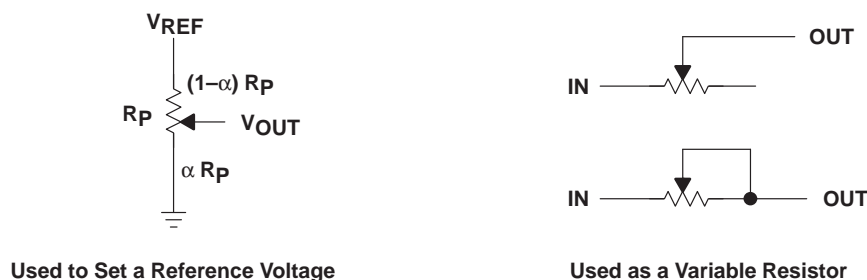


Figure 2. Potentiometer Applications

$$R_P = \alpha R_P + (1 - \alpha)R_P = R_P \quad (2)$$

The pot is divided into two parts α and $(1-\alpha)$.

$$V_{OUT} = V_{REF} \frac{\alpha R_P}{(1 - \alpha)R_P + \alpha R_P} = \alpha V_{REF} \text{ for } R_L \gg R_P \quad (3)$$

This is a very popular application for pots, and the reference input voltage must be very stable because the circuit is controlled by the reference. The reference voltage source should be well decoupled with a good grade capacitor to localize noise and keep it from spreading to other circuits.

Variable resistor applications can be very subtle, but the first thing to remember is that the pot has a limited current carrying capability. Do not connect the variable resistor configuration between the power supply and ground even if it connects through a semiconductor junction. When the variable resistor configuration is connected across a power supply or battery (even through a semiconductor junction), a series resistor must be inserted in the circuit to limit the current flow to a safe value.

Capacitors

The capacitor impedance is a function of frequency; at low frequencies the capacitor blocks signals, and at high frequencies the capacitor passes signals. Depending on the circuit connection, the capacitor can pass the signal to the next stage, or it can shunt it to ground. The impedance of a capacitor varies with frequency as shown in equation 4.

$$X_C = \frac{1}{2\pi f C} \quad (4)$$

All capacitors have a self-resonant frequency where the parasitic lead and dielectric inductance resonates with the capacitor in a series resonant circuit. Essentially, the capacitor impedance decreases until it reaches self-resonance where it is minimum impedance. The capacitor goes to lunch at frequencies higher than self resonance because the parasitic inductance causes it to become inductive, increasing the impedance; hence, capacitors are not dependable near their self-resonant frequency.

Aluminum electrolytic capacitors have a very low self-resonant frequency, so they are not effective in high frequency applications above a few hundred kHz. Tantalum capacitors have a mid range self-resonant frequency, thus they can be used up to several MHz. Beyond several MHz, ceramic and mica capacitors are the best choice because they have self-resonant frequencies ranging into the hundreds of MHz. Beware; there are a lot of inexpensive ceramic capacitors on the market with poor high-frequency performance.

Very low frequency and timing applications require another set of stable capacitors. The dielectric of these types of capacitor are made from paper, polypropylene, polystyrene, and polyester. These capacitors have low leakage current, low dielectric absorption, and they come in large values.

Referring to Figure 3, L models the lead and internal inductance of the capacitor. Except for dielectric materials such as ceramic and mica, the internal inductance is dominant at high frequencies. In high frequency capacitors the lead inductance can be approximated as 1/12 nH per foot. The combination of internal and lead inductance causes the capacitor to become self-resonant, and at frequencies above resonance the capacitor will appear to be an inductor. High-frequency applications demand capacitors with high self-resonant frequencies and short leads which is why surface-mount capacitors are used so often in high frequency circuit design.

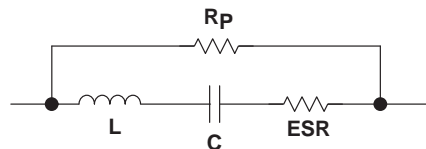


Figure 3. Capacitor Equivalent Circuit

The actual value of the capacitor is C. Equivalent series resistance (ESR) is the effective resistance of the capacitor at the operating frequency. It is an important parameter when high currents are involved. Power supply filter design requires low ESR capacitors because voltage is dropped across the ESR, and the current flowing through the capacitor causes power dissipation resulting in self heating. ESR is not an important parameter in the design of high frequency or signal processing circuits, thus ESR is only specified for aluminum electrolytic and tantalum capacitors.

The parallel resistance of a capacitor is modeled by R_p . This resistance is a function of the operating voltage and capacitor temperature; hence, it drifts quite a bit. Electrolytic capacitors exhibit the lowest parallel resistance, and aluminum electrolytic capacitors are often modeled with a parallel current source in place of R_p . Other types of capacitors have a relatively high R_p ranging in the hundreds of megohms.

Inductors

The primary use for inductors is filtering. There are two very different types of filter inductors: the high current inductor wound around a large core is used in power supply filters, and low current air core inductors are used in signal filters. The impedance of an inductor varies with frequency as shown in equation 5.

$$X_L = 2\pi fL \quad (5)$$

High current inductors require cores to keep the losses within acceptable limits and to achieve high performance. The cores are big and heavy, so they are a large contributor to cost, weight, and size. Switching power supplies require extensive inductors or transformers to control the switching noise and filter the output voltage waveform.

Low current inductors are used for filters in signal processing circuits. Capacitors, used in circuits which simulate inductors, replace inductors where possible because they are less expensive and readily available, but there are a few applications that inductors excel in. An inductive/capacitive filter has sharper slopes than a resistive/capacitive filter, thus it is a more effective filter in some applications. In general, inductors are rarely seen outside power circuits.

The inductor model, see Figure 4, is rather simple consisting of the inductor, L , the series resistance, R_S , and the parallel capacitance, C_P . The series resistor lowers the Q , or quality factor of the inductor. Inductors are wound with wire whose size determines the series resistance. The wire size also determines the weight and number of turns that can be wound on a core, so series resistance versus inductance is always a compromise that the manufacturer must make. The parallel capacitance degrades the inductor performance at high frequencies because it turns the inductor into a parallel resonant circuit. The range of C_P values is very large because of the many sizes and shapes of inductors.

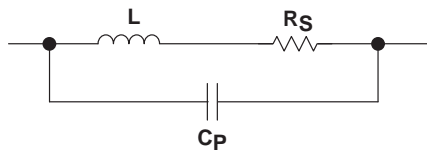


Figure 4. Inductor Equivalent Circuit

Signal or Rectifier Diodes

Diodes must be biased to be used, and often the circuit using the diode provides the bias. Forward biased diodes have the most positive voltage applied to their anode, while reversed biased diodes have the most positive voltage applied to their cathode. Forward biased diodes pass current (current is defined as the movement of positive charges) in the forward direction which is the direction of the arrow, and reverse biased diodes block current flow. Forward biased diodes exhibit a low resistance, and reverse biased diodes exhibit a high resistance.

It takes a small voltage to forward bias the diode, but as the current flow increases, its voltage drop quickly rises to approximately 0.6 volts for a silicon diode and 0.2 volts for a germanium diode. The voltage drop is a function of the bias current, but these approximations suffice for the majority of applications. Equation 6 is not an equation that you will use very much, but it describes the I/V relationship in a diode. Note that the I/V relationship is exponential.

$$I_F = I_{SAT} e^{\frac{qV_F}{KT}} \quad (6)$$

When the diode is forward biased, the voltage drop, V_F , is shown as a battery (see Figure 5). The diode resistance, r_e , is also a function of the forward current, and it is approximated by the equation $r_e = 26/I$, where I is in milliamps. This approximation of r_e holds over a wide current range. When the diode is reverse biased the forward current is zero, and the equation says that r_e equals infinity. This is not exactly true, but the relationship is too complicated for this discussion. A simple way out of the trap is to include the current source, I_L , which models a reverse biased leakage current. The leakage current is voltage and temperature sensitive, so it is best to use diodes which have very low leakage currents.

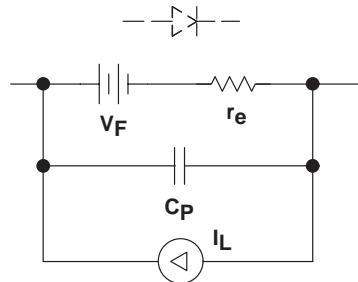


Figure 5. Diode Equivalent Circuit

A diode is used to make a positive peak detector by letting the signal forward bias the diode and storing the resultant voltage on a capacitor. Lesser voltages do not forward bias the diode, so they are ignored. When a diode is forward biased it is low resistance so it can pass a signal, and when it is reverse biased, the diode is high resistance thus it blocks the signal. The forward biased current is limited by connecting a resistor in series with the diode.

Diodes take a finite amount of time to turn on and turn off. Some of this time results from the carrier physics internal to the diode, and some of this time results from the parallel capacitance, C_P . Depending on the diode and the bias conditions, C_P ranges from a fraction of a pF for small switching diodes to a few hundred pF for power diodes. Remember, diodes have switching times that may have to be accounted for.

Component Tolerances

All passive components have initial tolerances, and no prudent engineer would design a circuit without considering tolerances induced by the circuit. The list of tolerances includes initial tolerance, temperature drift, aging, vibration, stress, and several others which are beyond the scope of this application note. The tolerance discussion is simplified by experience which yields rule of thumb tolerances which can be added to the initial tolerances.

Double the initial tolerance for resistors to allow a safety margin. Use 1% initial tolerance resistors as 2%, 2% initial tolerance resistors as 4%, and 5% initial tolerance resistors as 10%. There really is not much reason to use resistors with larger initial tolerances than 5%.

Capacitors, except for electrolytic and tantalum, follow the same rule as resistors. Both electrolytic and tantalum capacitors are polarity sensitive, so they must not be reverse biased even for short periods. Electrolytic capacitors have tolerances in the 20%, –80% percent range. Doubling these large tolerances is prohibitive, thus the application of the electrolytic capacitor determines its tolerance. Tantalum capacitors also need special care, and the application determines their tolerance, but doubling the initial tolerance works in most applications.

Miniature inductors used in high frequency work should have their initial tolerances tripled. Core inductors are extremely application sensitive, so no general rule can be given for their tolerances.

Summary

There are many different components which are not discussed. The components not covered include several types of diodes such as Schottky diodes, Zener diodes, tunnel diodes, selenium diodes, and others. The discussion does not lose much because of the components not covered, rather it enables us to focus on the components used in 99% of the applications.

Resistors control current flow by resisting it. A capacitor's impedance is a function of frequency; it blocks dc and passes ac signals. Inductors are seldom used. Diodes block reverse current and pass forward current. When diodes are forward biased their resistance is low, and when they are reverse biased their resistance is high.

All components have initial and application tolerances which must be accounted for.