

# Introduction to the Fundamentals of Analog Circuit Design

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**Abstract:** This paper introduces the basic compositions of analog circuits design integrated with adequate electronic components and describes the analog design process of electronic circuits as that of taking a series of important properties, desired performance specifications, process capabilities and skillfully devising a working system that possesses those properties. In addition, the fundamentals of Ohm's law and basic analog circuit concepts, main circuits of voltage and current divider calculations, capacitance calculations, inductance calculations, analog amplifier circuits calculations, and circuits types of analog RC filters are also described in this paper.

**Keywords:** Analog Circuit, Ohm's Law, Voltage, Divider, Capacitance, Inductance, Analog Amplifier Circuits, Analog RC Filters

## 1. Introduction

Analog design is part of electronic integrated circuit design and focuses on signal fidelity, amplification, and filtering. The task of analog design, in a nutshell, is to make this complex integrated circuitry perform consistently. However, digital design packs dense circuitry into microprocessors and maximizes desired circuit efficiency in memory and application-specific chips.

The designing process of analog circuits is being involved in creating the initial design, using computer programs to model assumptions, create system designs and run design-level tests on them. In addition, this process provides testing and recording variability in the electronic components, placing amplifiers and filters to keep the signals clean, uses techniques such as matching resistors to cancel out variations or segmenting and matching the segments in a large resistor and analyzes the circuit's performance under many situations with testing software.

The analog design has not yet yielded every design needed, because integrated circuits keep changing and growing, so a modern integrated circuit may hold several hundred millions of electronic components on a fingernail-sized area. This complexity means that hundreds of rules apply regarding design specifications, compatible layers and the appropriate tests to measure performance. Further, the manufacturing process is so sensitive that supposedly identical chips may do things differently. These variations in an integrated circuit's processors can cause fatal errors during the designing process.

## 2. Ohm's Law and Basic Analog Circuit Concepts

Ohm's law as the fundamental of all electronics is an equation that describes the above relationship between the voltage potential, the current flowing in the circuit, and the resistance of a circuit, which simple representation is illustrated in **Figure 1**. The power dissipated in a load resistance is defined as the product of the current and the voltage.

The electronic element resistance (R) can be defined as the characteristic of a medium that opposes the flow of electrical current through itself. The unit of resistance is ohm which is represented by the Greek letter  $\Omega$  (Omega). The power value associated with resistance is quantified as the amount of power that the resistor can dissipate as heat without overheating itself. The current (I) generated by voltage ( $V = I \times R$ ) through the resistor ( $R = V/I$ ) is defined as:

$$I = V/R \quad (1)$$

At this point, for an 1 Megaohm (M $\Omega$ ) resistance, the current resulting from the application of 10 Volts (V) would be 10 microamperes ( $\mu$ A).

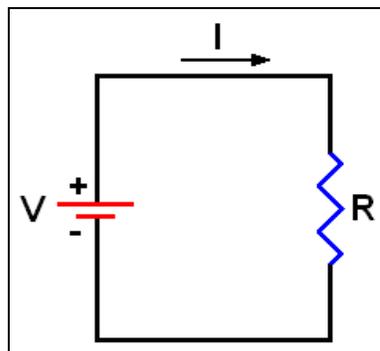


Fig. 1. Simple Representation of Ohm's Law

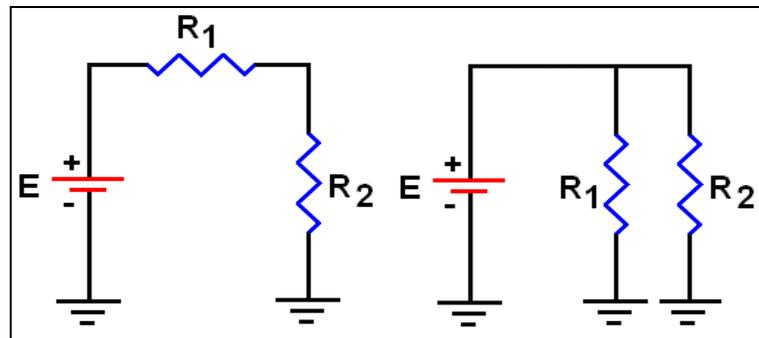


Fig. 2. Series and Parallel Voltage Configuration

Other relationships for power ( $P$ ) dissipated in ( $R$ ) can be easily derived from this by applying Ohm's law using substitution as follows:

$$P = I \times V = V^2/R = I^2 \times R \quad (2)$$

To calculate the value of resistance ( $R$ ) that will result in 10 Watts ( $W$ ) with 10 Volts ( $V$ ) applied to it, and because that  $P = V^2/R$ , the value of  $R = V^2/P$ . However, if the resistance is  $100/10$ , or 10 ohms ( $\Omega$ ), so 10  $V$  applied to 10  $\Omega$  will yield 10  $W$ . Any time two of the parameters ( $V$ ,  $R$ , or  $P$ ) are numerically the same, the third one will be the same. Thus, a common way to measure resistance is by using the universal or special measuring instruments used in maintenance or design electronic circuits.

### 3. Voltage and Current Divider Calculations

In many circuits, it is necessary to obtain a voltage not available from the main power source. Rather than have multiple power sources for all needed voltages, it will be possible to derive other voltages from the main power source. In most cases, the needed voltage is less than the voltage from the main source, so for this can be used resistors in an appropriate configuration to reduce the voltage from the power source, for use in a small circuit. If is precisely known both the voltage and current required, it can be simply connect a resistor in series with the power source, with a value calculated in accordance with Ohm's Law. This resistor will drop some of the source voltage, leaving the right amount for the actual load, as shown to the right.

In electronics, a voltage divider, also known as a potential divider is a passive linear circuit that produces an output voltage ( $V_{out}$ ) that is a fraction of its input voltage ( $V_{in}$ ). Voltage division is the result of distributing the input voltage among the components of the divider. A simple example of a voltage divider is two resistors connected in series, with the input voltage applied across the resistor pair and the output voltage emerging from the connection between them, which circuit is shown in **Figure 2 (Left)**.

Resistor voltage dividers are commonly used to create reference voltages, or to reduce the magnitude of a voltage so it can be measured, and may also be used as signal attenuators at low frequencies. Thus, for direct current and relatively low frequencies, a voltage divider maybe sufficiently accurate if is made only of the resistors, where the frequency response over a wide range is required, such as in an oscilloscope probe, a voltage divider may have capacitive elements added to compensate load capacitance. In electric power transmission, a capacitive voltage divider is used for measurement of high voltage.

When two resistors are connected in a series configuration, they must share the applied voltage and the same current flows through both of them. The formula used to calculate the applied voltage is:

$$E_1 = R_1 \times I \quad (3)$$

$$I = E/R_{EQ}; \quad \text{and} \quad R_{EQ} = R_1 + R_2 \quad (4)$$

$$E_2 = R_2 \times I = R_2/I = R_2 (E/I R_{EQ} = R_2 [E/(R_1 + R_2)] = E [R_2/(R_1 + R_2)] \quad (5)$$

$$E = E_1 + E_2 = I (R_1 + R_2) \quad (6)$$

where  $E_1$  = Voltage drop across  $R_1$ ;  $E_2$  = Voltage drop across  $R_2$ ; and  $R_{EQ} = R$  equivalent.

Current divider calculation is performing when two resistors are connected in parallel configuration, so the same voltage is across each of them, shown in **Figure 2 (Right)**. The amount of current flowing through them depends on the value of the resistances.

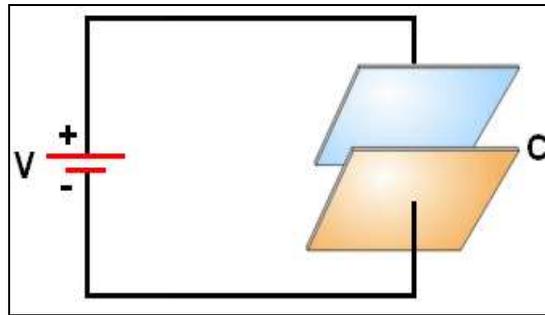


Fig. 3. Example of Capacitance Circuit

In electronics, a current divider is a simple linear circuit that produces an output current that is a fraction of its input current. Namely, a current divider circuit is a circuit which divides the input current to various branches in a certain ratio. A simple arrangement of two or more resistors in parallel can be considered as a current divider circuit. A current divider circuit contains various impedances in parallel.

To be specific, if two or more impedances are in parallel, the current that enters the combination will be split between them in inverse proportion to their impedances, according to ohm's law. It also follows that if the impedances have the same value the current is split equally. Thus, a current divider is a simple linear circuit or device which divides the total input current to various paths or loads in fractions of the input current. The diagram shown in **Figure 2 (Right)** depicts two resistors in a parallel configuration, which is expressed as:

$$I = I_1 + I_2 = (E/R_1) + (E/R_2) = E [(1/R_1) + (1/R_2)]; \text{ and } R_{EQ} = 1/(1/R_1) + (1/R_2) = (R_1 \times R_2)/(R_1 + R_2) \quad (7)$$

$$E = I_1 \times R_1 = I_2 \times R_2 = I \times R_{EQ} \quad (8)$$

Digital Multi Meter (DMM) instruments are the most common measurement devices found and used in automated test systems. They are usually simple to use and are often low-cost instruments. Generally, these instruments have built-in conditioning that provides the following values: a) High resolution, commonly measured in digits); b) Multiple measurements (volts, current, resistance, etc) and c) Isolation and high voltage capabilities.

#### 4. Capacitance Calculations

Capacitors store energy in the form of electrical charge. The amount of charge that the capacitor can hold depends on the area of the two plates in the figure above and the distance between them. Large plates with a small distance between them have a higher capacity to a hold charge. The electric field between the plates of a capacitor resists changes in applied voltage. Capacitors decrease their resistance with frequency.

Capacitors vary in shape and size, but the basic configuration is two conductors carrying equal but opposite charges, which circuit is shown in **Figure 3**. Capacitors have many important applications in electronics and electrical engineering. Some examples include storing electric potential energy, delaying voltage changes when coupled with resistors, filtering out unwanted frequency signals, forming resonant circuits and making frequency-dependent and independent voltage dividers when combined with resistors. However, some of these applications will be discussed in later chapters.

The unit of capacitance is Farad which is represented by the letter F. The formula to calculate capacitance is:

$$C = Q/V \text{ [F]} \quad (9)$$

where C = Capacitance in farads, Q = Accumulated charge in coulombs and V = Voltage difference between the plates.

The limiting factor for the size of the capacitor is the power supply (V), which is intended to use. The maximum power output from the coil requires the voltage to recharge the capacitor, fully, each mains half-cycle. This will occur when the impedance of the voltage matches that of the primary cap, at a line frequency of 50Hz or 60Hz. Thus, the maximum value of the capacitor or impedance can be calculated as follows:

$$Z = V/I \quad (10)$$

where V = voltage output; and I = current output in Amperes (A).

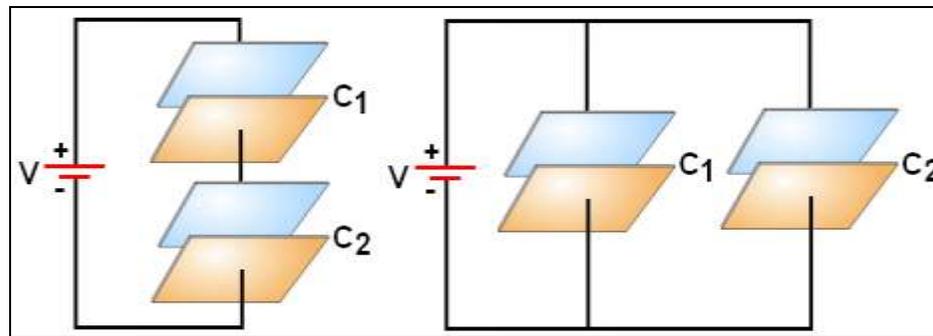


Fig. 4. Series and Parallel Capacitor Configuration

In **Figure 4 (Left)** is illustrated the common configuration that represents two capacitors in series. Since the capacitance of a capacitor is inversely proportional to the distance between the plates, the total capacitance ( $C_T$ ) of any number of capacitances can be calculated by the following:

$$C_T = 1 / [(1/C_1) + (1/C_2) + (1/C_3)] + \dots \tag{11}$$

The values of capacitance (C) and voltage (V) for two capacitors connected in series are as follows:

$$C_1 = Q/V_1; C_2 = Q/V_2; V_1 = Q/C_1 \text{ and } V_2 = Q/C_2 \tag{12}$$

The total values of voltage and capacitance equivalent are as follows:

$$V = V_1 + V_2 = Q/C_{EQ} \text{ and } C_{EQ} = 1 / [(1/C_1) + (1/C_2)] = C_1 \times C_2 / C_1 + C_2 \tag{13}$$

In **Figure 4 (Right)** is depicted configuration that represents two capacitors in the parallel circuit. Thus, each capacitor charges to the same applied voltage. Total capacitance equals the sum of the individual capacitances of the capacitors. The amount of charge that can be placed on a capacitor is proportional to the voltage (V) and capacitance (C) pushing the charge onto the positive plate. In the proper manner, the larger the potential difference (V) between the plates, the larger the charge (Q) on the plates:

$$Q_1 = C_1 \times V; Q_2 = C_2 \times V; Q = Q_1 + Q_2 = V (C_1 + C_2) \text{ and } C_{EQ} = C_1 + C_2; \text{ where } C_{EQ} = C \text{ equivalent} \tag{14}$$

### 5. Inductance Calculations

Inductance is defined as the amount of voltage dropped across the inductor for a given rate of change of current flowing through it. Inductors increase their resistance with frequency. The unit of inductance is Henry which is represented by the letter H.

In **Figure 5 (Left)** is shown a series configuration of two inductors, so when two inductors are connected in series then their total inductance equals the sum of individual inductances.

$$L_1 = L_2 = E \times di/dt; \text{ where } L_T = L_1 + L_2 \text{ and } di/dt = \text{Instantaneous rate of change of current over time (A/sec).}$$

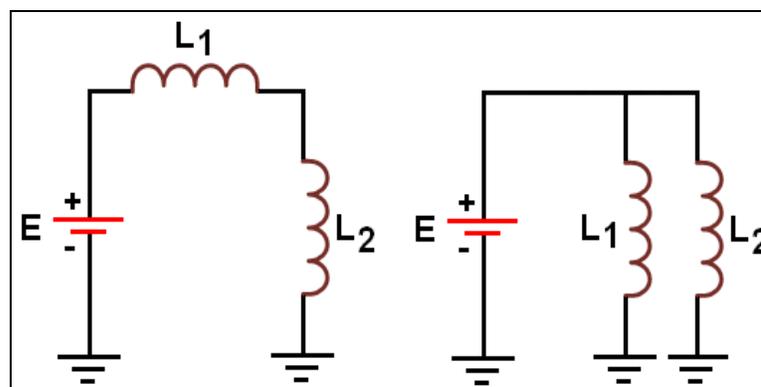


Fig. 5. Series and Parallel Inductor Configuration

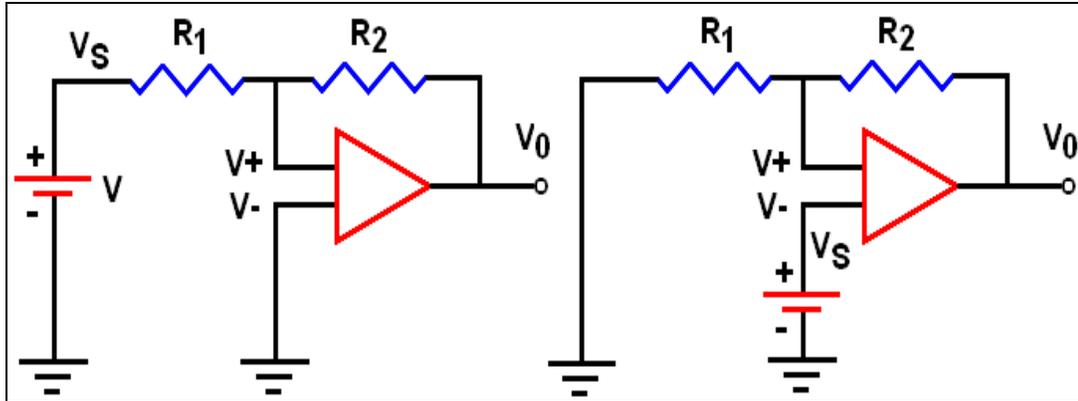


Fig. 6. Basic Inverting and Non-inverting Amplifiers

However, in the real world if we consider mutual inductance where magnetic field of each inductor affects the other coil then the total inductance can be calculated using the formula below:

$$L_T = L_1 + L_2 \pm 2M; \text{ where } M = \text{mutual inductance between the two coils.} \tag{15}$$

The instantaneous voltage across the inductor (V) is as follows:

$$V = L (di/dt).$$

In **Figure 5 (Right)** is illustrated a parallel configuration of two inductors. When two inductors are connected in a parallel configuration, mutual inductance needs to be considered. Also, the mutual inductance will be either added or subtracted from the self-inductance of each coil since the current has two paths to flow in. The total inductance can be calculated using the formula below:

$$L_T = [(L_1 \times L_2) - M^2] / [(L_1 + L_2) - 2M] \tag{16}$$

At this point, the modern digital multimeters today provide universal measurement capability by offering engineers the 20 most common automated test measurements, including voltage, current, capacitance, inductance, temperature and resistance.

### 6. Analog Amplifier Circuits

Operational Amplifiers (OA) are highly stable, high gain DC difference amplifier circuits. Since there is no capacitive coupling between their various amplifying stages, they can handle signals from zero frequency (DC signals) up to a few hundred kHz. Their name is derived by the fact that they are used for performing mathematical operations on their input signals. Here will be introduced two types of amplifiers:

**1. Inverting Amplifier** – An inverting is as simple as it sounds and it simply reverses the polarity of the input signal, shown in **Figure 6 (Left)**. For example, if the voltage going into the amplifier is positive, it is negative when it comes out. Calculating the output signal voltage and the gain of an inverting amplifier is as follows:

$$V_0 = A (V_+ - V_-); V_S - V_1/R_1 = V - V_0/R_2 \text{ since } V_1 = V - 0 \text{ (Virtual ground)} \tag{17}$$

$$V_S/R_1 = - V_0/R_2 \text{ and Gain} = V_0/V_S = - R_2/R_1 \tag{18}$$

**Non-Inverting Amplifier** – The gain of the amplifier is determined by the ratio of  $R_1$  and  $R_2$ . Calculating the gain of a non-inverting amplifier is as follows:

$$V_0 \times R_1 = V_S \times R_1 + V_S \times R_2 \text{ and } R_1 (V_0 - V_S) = V_S \times R_2 \text{ where:} \tag{19}$$

$$V_0/V_S - 1 = R_2/R_1 \tag{20}$$

$$\text{Gain} - 1 = R_2/R_1 \text{ and Gain } 1 = R_2/R_1 \text{ where: Gain} = V_0/V_S \tag{21}$$

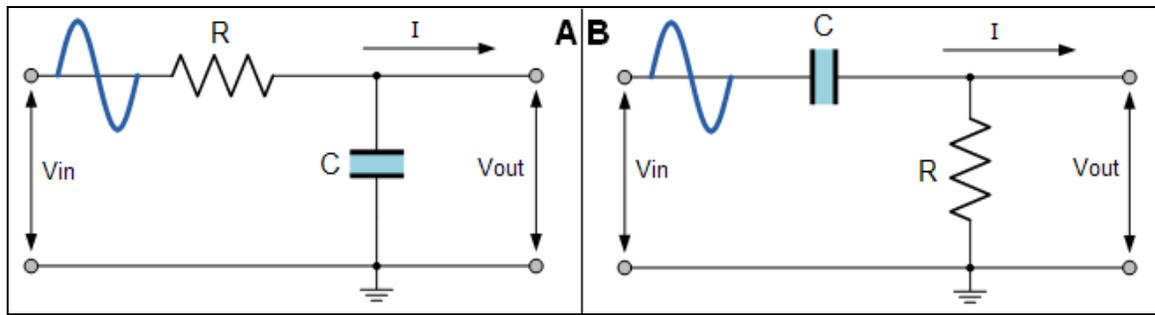


Fig. 7. Simple RC Low and High Pass Filters

The summing amplifier is a logical extension of the previously described circuit, with two or more inputs. The difference amplifier precisely amplifies the difference of two input signals. The differentiator generates an output signal proportional to the first derivative of the input with respect to time. The integrator generates an output signal proportional to the time integral of the input signal.

## 7. Analog RC Filters

**1. RC Low Pass Filter** – A common circuit to attenuate high-frequency components in an analog signal is the RC Low Pass Filter. In **Figure 7 (A)** is shown that  $V_{in}$  is the applied voltage and the voltage  $V_{out}$  across  $C$  is the output:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}, \text{ where } R_1 + R_2 = R_T \quad (22)$$

This filter passes low frequency and DC signals to the output, but blocks out high-frequency signals, which single-pole RC low pass is:

$$t = R \times C \text{ where } F_{adb} = 1/2\pi t \quad (23)$$

This circuit arrangement can also be thought of as a frequency dependant variable potential divider circuit similar to the one we looked at in the Resistors tutorial. In that, tutorial we used the following equation to calculate the output voltage for two single resistors connected in series.

**2. RC High Pass Filter** - A circuit that attenuates low-frequency components in an analog signal is called an RC High Pass Filter, shown in Figure 7 (B). Notice that the circuit is similar to the one above, but  $V_{out}$  is now measured across  $R_1$ . The cut-off frequency point ( $f_c$ ) for a first-order highpass filter can be found using the same equation as that of the low pass filter, while the equation for the gain ( $A_V$ ) and phase shift ( $\phi$ ) is modified slightly to account for the positive phase angle as shown below:

$$A_V = V_{out}/V_{in}; \quad f_c = 1/4\pi RC; \quad \text{and} \quad \phi = \arctan 1/4\pi fRC \quad (24)$$

In this circuit arrangement, the reactance of the capacitor is very high at low frequencies so the capacitor acts like an open circuit and blocks any input signals at  $V_{in}$  until the  $f_c$  value is reached. Above this cut-off frequency point the reactance of the capacitor has reduced sufficiently as to now act more like a short circuit allowing all of the input signals to pass directly to the output as shown below in the filters response curve.

## 8. Conclusion

This article is introducing the fundamentals of analog circuit and solutions that anyone interested in this technique can apply in today's demanding designs. Analog circuits for electronic system design are more important these days in the 21st century than ever before. In fact, with the very rapid development and implementation of modern digital techniques and technologies, cellular systems, complex industrial and automotive systems, designers are challenged to develop more sophisticated analog solutions. The structural design methodology of analog circuit can be the base for break-through in all areas of analog, and is especially efficient in power management and instrumentation IC design. In fact, everything a person sees, hears and perceives in life is analogous, from sound, music and seismic activity to visual perception, voice recognition and energy delivery. As a result, all electronic systems must interface with the world via analog electronics, that challenge analog engineers with a demand for small, chip-integrated and battery-powered communication devices.

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