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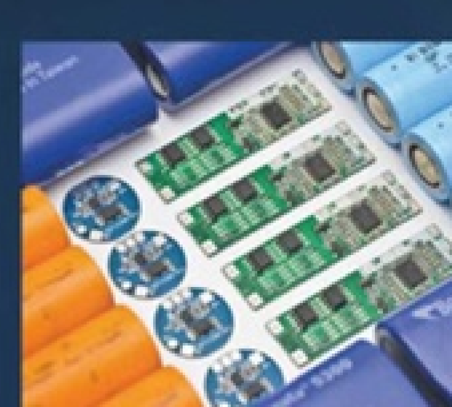

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BASICS OF ANALOG CIRCUIT DESIGN

STOJCE DIMOV ILCEV FROM DURBAN UNIVERSITY OF TECHNOLOGY IN SOUTH AFRICA DESCRIBES THE ANALOG DESIGN PROCESS, WHICH BALANCES IMPORTANT PROPERTIES, DESIRED PERFORMANCE SPECIFICATIONS AND CAPABILITIES

Analog design is part of integrated circuit (IC) 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 and most efficiently.

The design process for an analog circuit involves creation of the intial design, the use of software programs to model and verify it, then construction of the system and thorough testing. The process will involve a lot of tweaking with various electronic components, such as placing amplifiers and filters at specific points in the circuit to keep the signals clean, or using matching resistors to cancel out signal variations.

Modern ICs may consist of several hundred million electronic components in the tiniest of areas, a complexity that means that hundreds of rules apply regarding their 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. If not considered, these variations in an integrated circuit's processors can cause fatal errors during the design process.

The Basics

The electronic parameter resistance (R) can be defined as the characteristic of a material that opposes flow of electrical current through itself. The unit of resistance is the ohm, represented by the Greek letter Ω (Omega). The power value associated with resistance is quantified as the amount of power in watts (W) that a resistor can dissipate as heat without overheating. The current (I) generated by the voltage (V) through the resistor (R) is defined as:

$I = V/R$; where $V = I \times R$ and $R = V/I$

At this point, for a 1 megohm (MΩ) resistance, the current resulting from the application of 10 volts (V) would be 10 microamperes (μA).

Ohm's law is the fundamental equation that describes the above relationship between the voltage, the current flowing in a circuit and the resistance of the circuit; its simple representation is shown in Figure 1. The power dissipated in a load resistance is defined as the product of current and voltage.

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

$P = I \times V = V^2/R = I^2 \times R$

To calculate the value of the resistance R, and since $P = V^2/R$, the equation is $R = V^2/P$. So, if R is 100/10, or 10Ω, the 10V applied to 10Ω will yield 10W. Whenever any two of the parameters V, R or P are numerically the same, the third will be the same too.

Voltage And Current Divider Calculations

Many circuits require voltage different from that of the main power source. But rather than have multiple power sources, it is possible to derive other voltages from the main power source by connecting resistors in an appropriate configuration and of different values (see Figure 2).

In electronics, a voltage divider, also known as a potential

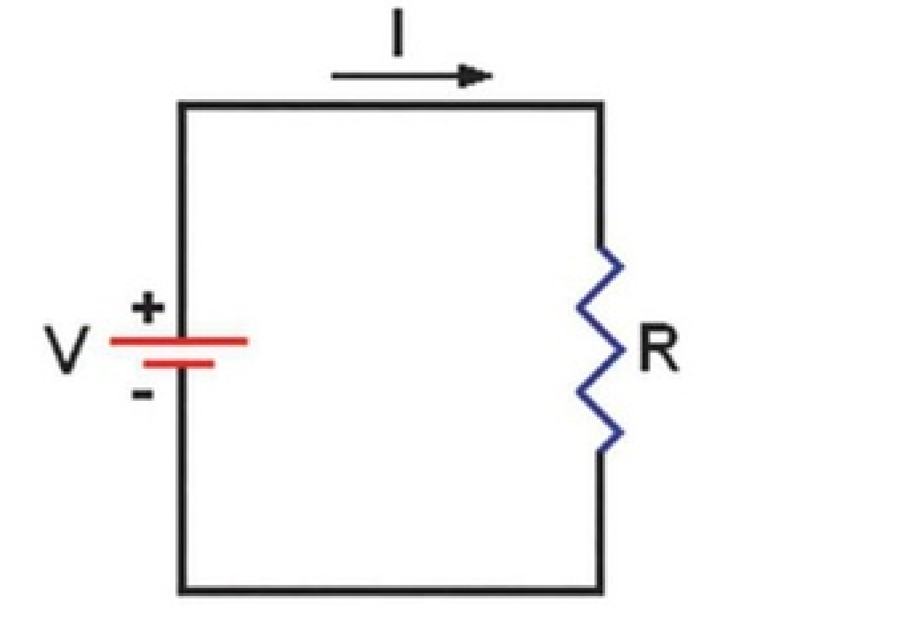


Figure 1: Graphic representation of Ohm's law

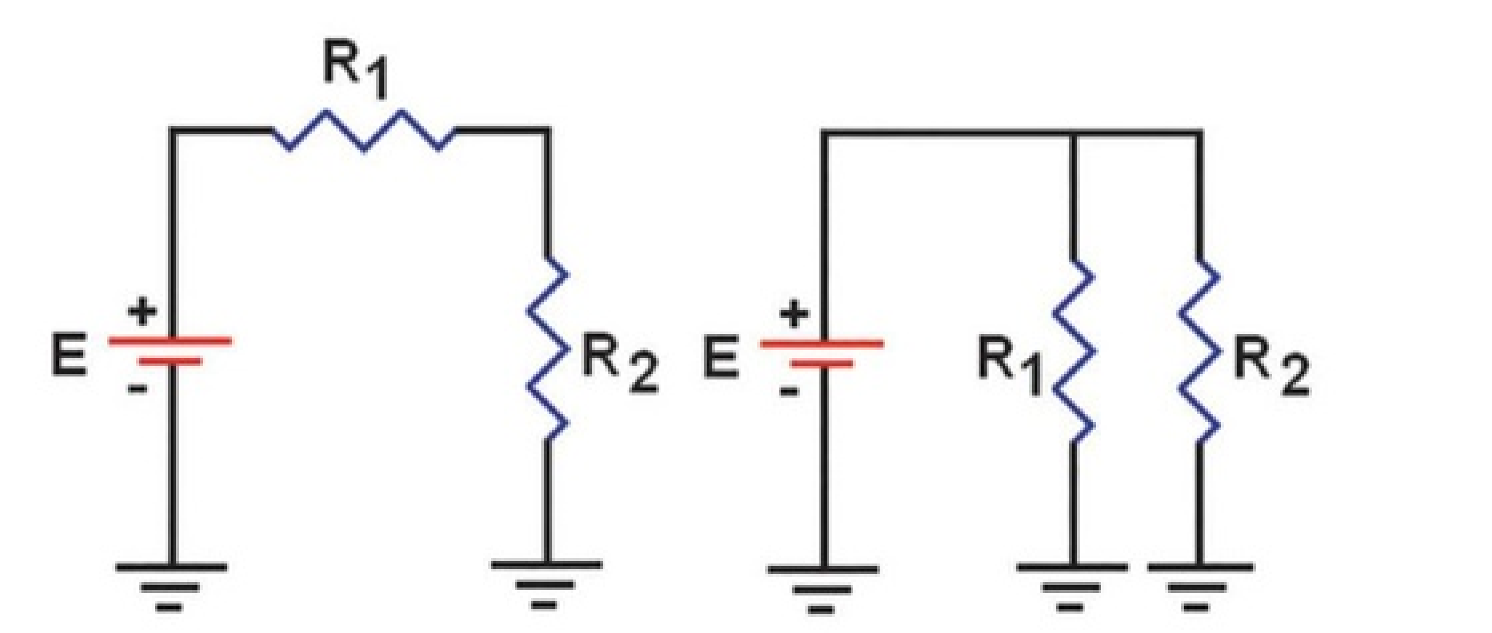


Figure 2: Series and parallel voltage configuration

Figure 3: Example of a capacitor circuit

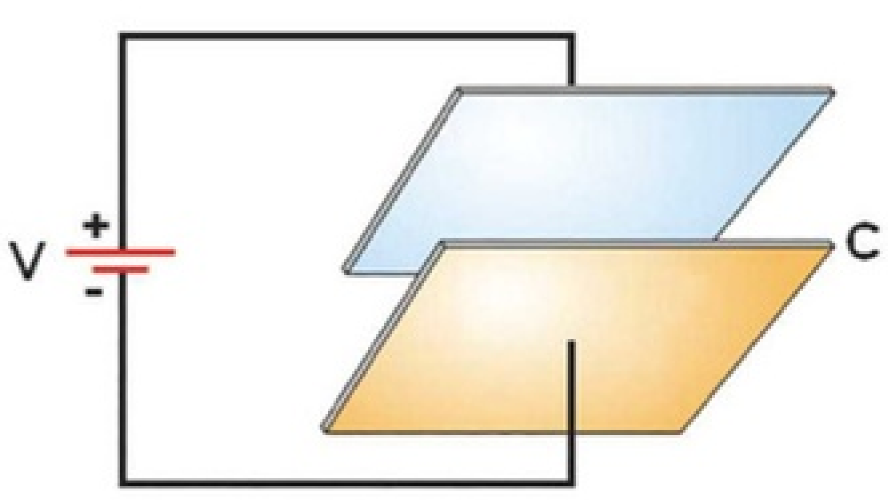
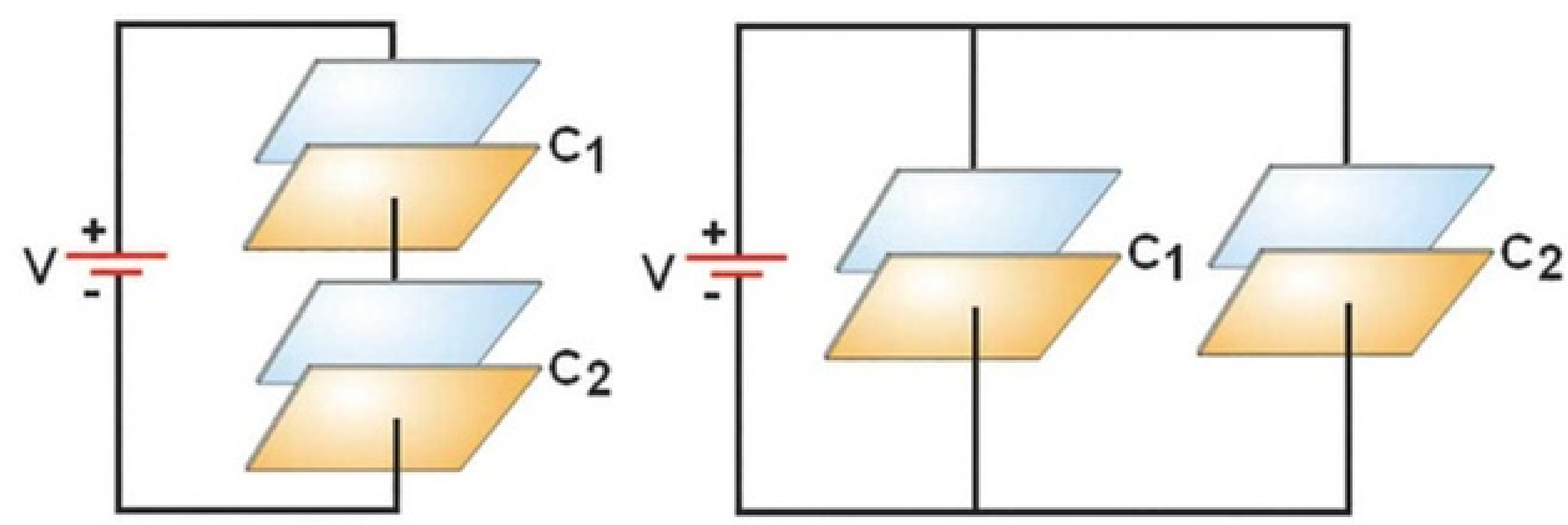


Figure 4: Series and parallel capacitor configurations



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 results from distributing the input voltage among the components of the divider. A simple example of a voltage divider is two resistors connected in series (Figure 2, left), with the input voltage applied across them and the desired voltage (voltage drop) produced across each resistor.

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

When two resistors are connected in series, they divide the applied voltage and the same current flows through both of them. The equation used to calculate the resultant voltages is:

$E_1 = R_1 \times I$ (E_1 = voltage drop across R_1); and

$E_2 = R_2 \times I = R_2/I$ (E_2 = voltage drop across R_2);

where:

$R_{EQ} = R_1 + R_2$; $E = E_1 + E_2 = I (R_1 + R_2)$ and $I = E/R_{EQ}$;

where:

$E_2 = R_2/I = R_2 (E / I R_{EQ}) = R_2 [E / (R_1 + R_2)] = E [R_2 / (R1 + R_2)]$

A current divider calculation is performed when two resistors are connected in parallel, with the same voltage across each, shown in Figure 2 on the right. The amount of current flowing through them depends on the resistor values.

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 which divides its input current into various branches in a certain ratio. A simple arrangement of two or more resistors in parallel can be considered 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 are equal the current is split equally. Thus, a current divider is a simple linear circuit or device which divides the total input current into various paths or loads as fractions of the input current. Figure 2 on the right shows two resistors in parallel, expressed as:

$I = I_1 + I_2 = (E/R_1) + (E/R_2) = E [(1/R_1) + (1/R_2)]$ where:

$E = I_1 \times R_1 = I_2 \times R_2 = I \times R_{EQ}$ and $R_{EQ} = 1/(1/R_1) + (1/R_2) = (R_1 \times R_2)/(R_1 + R_2)$; where R_{EQ} = R equivalent

The digital multimeter (DMM) is the most common measurement device used in automated test systems. It is very simple to use and is often low cost.

Generally, DMMs have built-in conditioning that provides the following properties: (a) high resolution, commonly expressed as "digits of resolution"; (b) multiple measurements (volts, current, resistance, etc); and (c) isolation and high-voltage capabilities.

Capacitance Calculations

Capacitors store energy in form of electrical charge. The amount of charge a capacitor can hold depends on the area of its two plates (as shown in Figure 3) and the distance between them. Large plates close together have a higher capacity to hold charge. The electric field between the plates of a capacitor resists changes in the applied voltage.

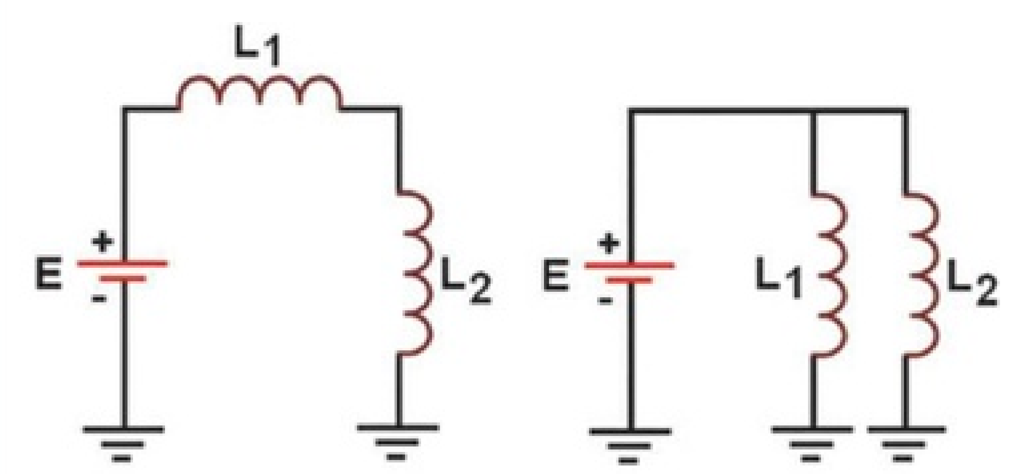


Figure 5: Series and parallel inductor configurations

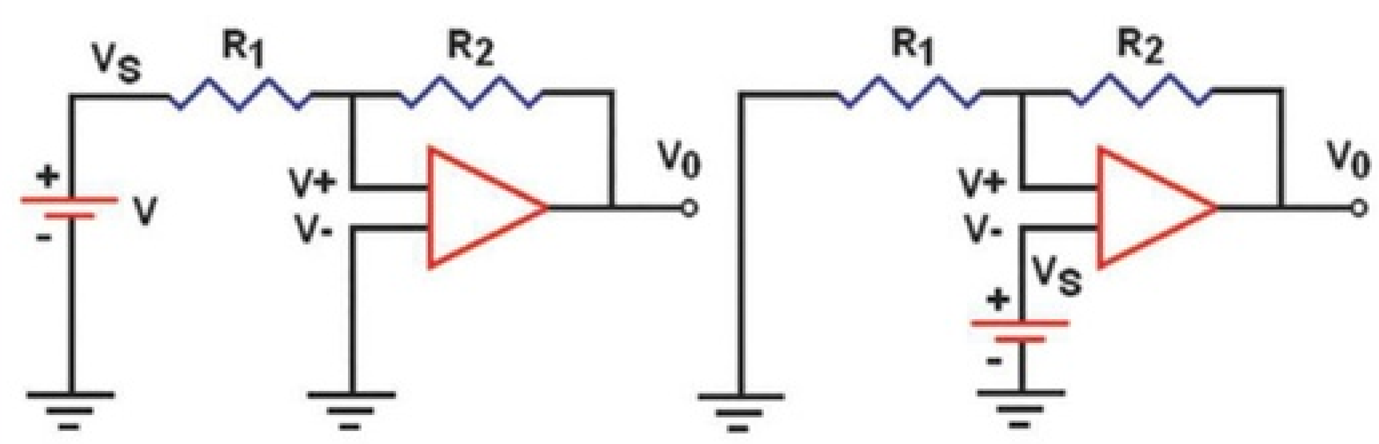


Figure 6: Basic inverting and non-inverting amplifiers

Capacitors decrease their resistance with frequency. They vary in shape and size, but their basic configuration is that their two conductors carry equal but opposite charges. They have many important applications in electronics and electrical engineering, including storing energy, delaying voltage changes when coupled with resistors, filtering out unwanted frequency signals, forming resonant circuits and frequency-dependent and -independent voltage dividers when teamed with resistors.

The formula to calculate capacitance is as follows; the capacitive unit is the farad (F):

$$C = Q/V$$

where C = capacitance in F, Q = accumulated charge in coulombs (C) and V = voltage difference between the plates.

The limiting factor for capacitor size is the power supply (V). The voltage recharges the capacitor, fully, each supply half-cycle. This will occur when the impedance of the voltage matches that of the primary cap, at the line frequency of 50Hz or 60Hz, for instance. So, maximum capacitor value or impedance can be calculated as $Z = V/I$; where V = voltage output and I = current output in amperes (A).

Figure 4 (left) shows two capacitors in series. Since the capacitance of a capacitor is inversely proportional to the distance between its plates, the total capacitance (C_T) of any number of capacitances in series can be calculated with:

$$C_T = 1/[(1/C_1) + (1/C_2) + (1/C_3)] + \ldots$$

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

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

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

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

$$C_1 \times C_2/C_1 + C_2$$

Figure 4 (right) shows two capacitors in parallel, where each charges to the same applied voltage. Total parallel 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. So, the larger the potential difference (V) between the plates, the larger the charge (Q) on the plates:

$$Q_1 = C_1 \times V;\ Q_2 = C_2 \times V;\ Q = Q_1 + Q_2 = V\,(C_1 + C_2)$$

and

$$C_{EQ} = C_1 + C_2;\ \text{where } C_{EQ} = C_{equivalent}$$

Inductance Calculations

Inductance is defined as the amount of voltage drop across an inductor for a given rate of change of current flowing through it. Inductors increase their resistance with frequency. The unit of inductance is the henry (H).

Figure 5 (left) shows two inductors in series; total inductance is the sum of the individual inductances:

$L_1 = L_2 = E \times di/dt$; where $L_T = L_1 + L_2$ and di/dt = instantaneous rate of change of current over time (A/s).

However, in the real world, if we consider a mutual inductance where the magnetic field of each inductor affects the other, then the total inductance can be calculated using $L_T = L_1 + L_2 \pm 2M$; where M = mutual inductance between the two coils.

The instantaneous voltage across the inductor is $V = L\,(di/dt)$.

Figure 5 (right) shows two inductors in parallel. In such a configuration, their mutual inductance needs to be considered. Also, mutual inductance will be either added or subtracted from the self-inductance of each coil, since the current has two paths to flow through. Total inductance can be calculated using this equation:

$$L_T = [(L_1 \times L_2) - M^2]/\,[(L_1 + L_2) - 2M]$$

Modern-day digital multimeters provide universal measurement by offering engineers the 20 most common, automated, test measurements, including voltage, current, capacitance, inductance, temperature and resistance.

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) up to a few hundred kHz. Their name is derived from their use in performing mathematical operations on input signals. There are two types of amplifiers: inverting and non-inverting.

1. Inverting amplifier – "inverting" simply reverses the polarity of the input signal, as shown in Figure 6 (left). For example, if the voltage going into the amplifier is positive, it is negative when it comes out. To calculate the output signal voltage and the gain of an inverting amplifier:

$V_o = A\,(V^+ - V^-)$; $V_S - V_1/R_1 = V - V_o/R_2$
since $V_1 = V - 0$ (virtual ground)

$V_S/R_1 = - V_o/R_2$ and Gain $= V_o/V_S = - R_2/R_1$

2. Non-inverting amplifier, shown in Figure 6 (right) – The gain of the amplifier is determined by the ratio of R_1 and R_2. To calculate the gain of a non-inverting amplifier use:

$V_o \times R_1 = V_S \times R_1 + V_S \times R_2$ and $R_1\,(V_o - V_S) = V_S \times R_2$

where:

$V_o/V_S - 1 = R_2/R_1$

Gain $-1 = R_2/R_1$

and Gain $1 = R_2/R_1$ where: Gain $= V_o/V_S$

There are other functions of op-amps: The summing amplifier is a logical extension of the previously described circuit, with two or more inputs. A 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.

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. Figure 7 (A) shows that V_{in} is the applied voltage and the voltage V_{out} across C is the output:

$V_{out} = V_{in} \times R_2/R_1 + R_2$, where $R_1 + R_2 = R_T$

This filter passes low frequency and DC signals to the output, but blocks high frequency signals.

$t = R \times C$ where $F_{adb} = 1/2\pi t$

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. The cut-off frequency point (f_C) for a first-order high-pass 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 (φ) is modified slightly to account for the positive phase angle as shown below:

$A_V = V_{out}/V_{in}$; $f_C = 1/4\pi RC$; and $\varphi = \arctan 1/4\pi fRC$ ●

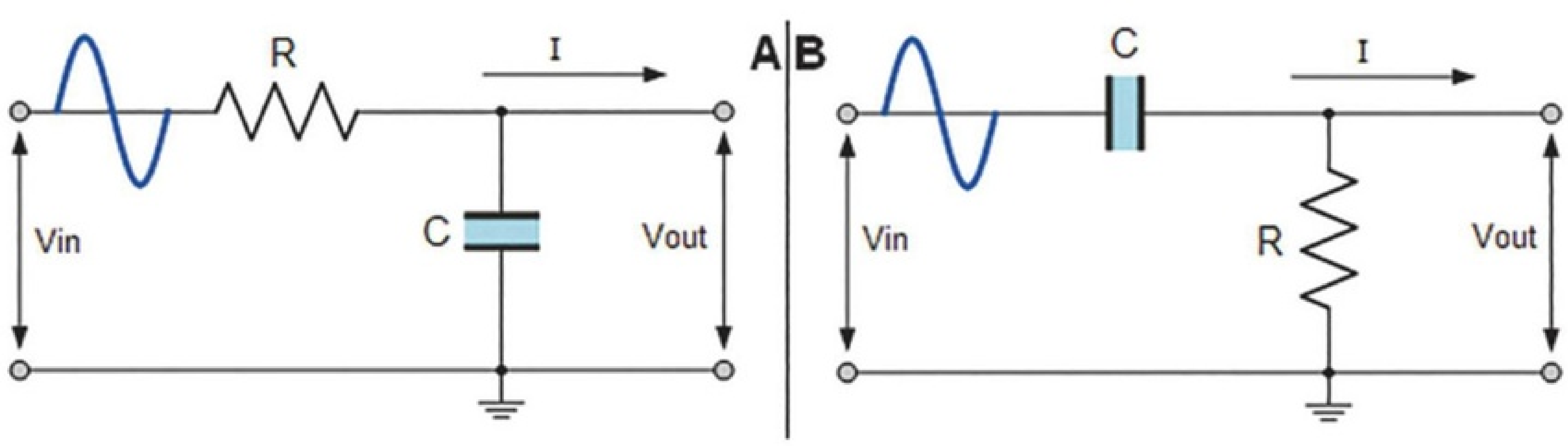


Figure 7: Simple RC low- and high-pass filters