Design and Simulation of Multi-Stage RC Low Pass Filter for Signal Conditioning

Abstract

Low pass filters play a crucial role in analog signal processing by allowing low-frequency components to pass while attenuating high-frequency noise. In this project, a multi-stage RC low pass filter is designed and simulated using the eSim EDA tool to enhance signal conditioning performance. The proposed design employs cascaded RC stages to achieve sharper attenuation and improved noise suppression compared to a single-stage filter. The circuit is analyzed using a sinusoidal input signal, and the results demonstrate effective attenuation of frequencies above the cutoff frequency, resulting in a smoother and more stable output waveform. This design is suitable for practical applications in communication systems and analog signal processing.

Introduction

In modern electronic and communication systems, maintaining signal integrity is a critical requirement. Signals are often affected by unwanted noise and high-frequency disturbances during transmission and processing, which can degrade system performance and accuracy. Therefore, effective signal conditioning techniques are essential to ensure reliable operation of electronic circuits.

A low pass filter (LPF) is one of the most fundamental analog circuits used for this purpose. It allows signals with frequencies lower than a specified cutoff frequency to pass through while attenuating higher-frequency components. Among various types of low pass filters, the RC (Resistor-Capacitor) filter is widely used due to its simplicity, cost-effectiveness, and ease of implementation.

However, a single-stage RC low pass filter provides only gradual attenuation beyond the cutoff frequency, which may not be sufficient for applications requiring sharper filtering characteristics. To overcome this limitation, multiple RC filter stages can be cascaded to form a multi-stage low pass filter. This configuration significantly improves attenuation of unwanted high-frequency components and results in a smoother output signal.

In this project, a multi-stage RC low pass filter is designed and simulated using the eSim open-source EDA tool. A sinusoidal input signal is applied to analyze the frequency response of the circuit. The cutoff frequency is determined based on selected resistor and capacitor values, and the output waveform is studied to evaluate the filtering performance.

This design demonstrates how cascading simple RC stages can enhance signal conditioning, making it suitable for practical applications such as communication systems, noise reduction circuits, and analog signal processing

Objectives

The main objectives of this project are:

- To design a basic RC low pass filter using resistor and capacitor components.

- To develop a multi-stage RC low pass filter by cascading multiple stages.

- To calculate the cutoff frequency based on selected values of resistance and capacitance.

- To simulate the designed circuit using the eSim EDA tool.

- To analyze the behavior of the filter using a sinusoidal input signal.

- To observe and compare input and output waveforms.

- To study the attenuation of high-frequency components.

- To evaluate the effectiveness of multi-stage filtering for signal conditioning applications.

Theory

A low pass filter (LPF) is an analog circuit that allows low-frequency signals to pass while attenuating high-frequency components. It is widely used in electronic systems for noise reduction and signal conditioning.

The simplest form of a low pass filter is the RC (Resistor-Capacitor) filter. It consists of a resistor connected in series with the input signal and a capacitor connected to ground. The output is taken across the capacitor.

The operation of the RC low pass filter is based on the frequency-dependent behavior of the capacitor. At low frequencies, the capacitive reactance is high, allowing the signal to pass to the output. At high frequencies, the capacitive reactance decreases, causing the signal to be bypassed to ground, thereby reducing the output amplitude.

The cutoff frequency (f_c) of an RC low pass filter is defined as the frequency at which the output voltage drops to approximately 70.7% of the input voltage. It is given by:

$$f_c = \frac{1}{2\pi RC}$$

Where:

- R is the resistance in ohms (Ω)
- C is the capacitance in farads (F)

In a single-stage RC filter, the attenuation of high-frequency signals is gradual. To achieve sharper attenuation and improved filtering performance, multiple RC stages can be cascaded to form a multi-stage low pass filter.

In a multi-stage configuration, the output of one stage is fed as the input to the next stage. This results in increased attenuation of high-frequency components and produces a smoother output waveform. The overall effect is an improved filtering response, making the circuit more effective for practical signal conditioning applications.

Note : The rate of attenuation increases with the number of stages, improving the selectivity of the filter.

Cutoff Frequency Calculation

For the designed RC low pass filter, the cutoff frequency is calculated using:

$$f_c = \frac{1}{2\pi RC}$$

Stage 1 :

- R1=2.2 kΩ
- C1=0.47 µF

$$f_{c1} = \frac{1}{2\pi \times 2200 \times 0.1 \times 10^{-6}} \approx 723\,Hz$$

Stage 2 :

- R2=2.2 kΩ
- C2=0.47 µF

$$f_{c2} = \frac{1}{2\pi \times 2200 \times 0.1 \times 10^{-6}} \approx 723\,Hz$$

The cutoff frequency of the designed RC low pass filter is approximately **723 Hz**. This means that frequencies below 723 Hz pass through the filter with minimal attenuation, while frequencies above 723 Hz are gradually reduced.

Circuit Design

The proposed circuit is a multi-stage RC low pass filter designed by cascading two individual RC filter stages. Each stage consists of a resistor and a capacitor, where the resistor is connected in series with the input signal and the capacitor is connected to ground.

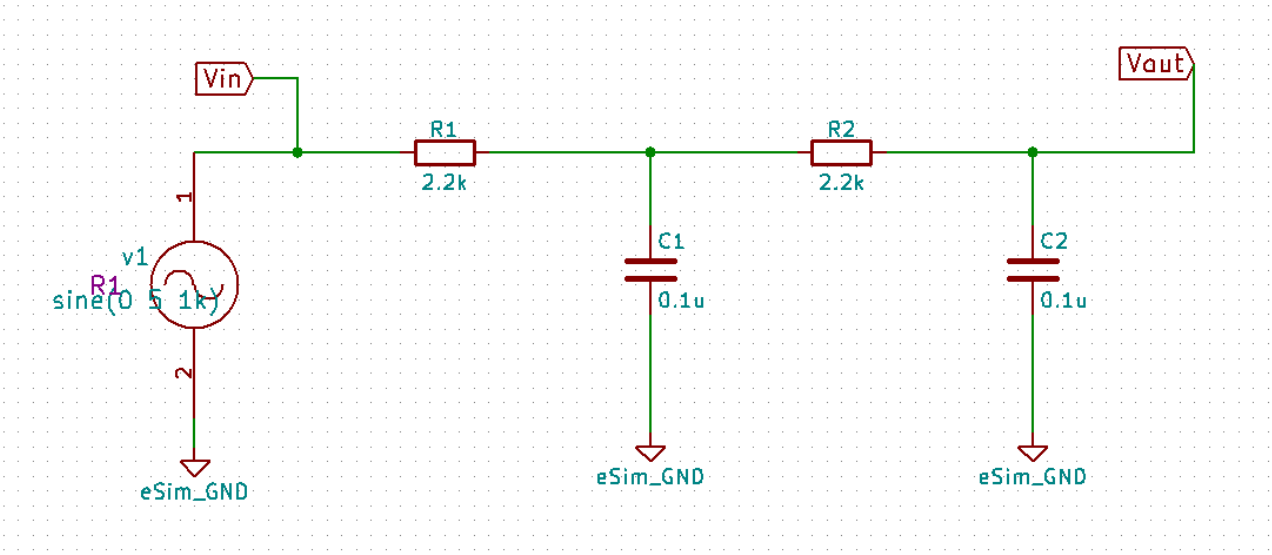
In the first stage, the input signal is applied across the resistor *R1* , and the capacitor *C1* is connected between the output node and ground. The output of this stage is then fed as the input to the second stage, which consists of resistor *R2* , and capacitor *C2* .

The final output of the circuit is taken across the capacitor *C2* of the second stage. This cascading of two RC stages enhances the overall filtering performance by increasing the attenuation of high-frequency components.

The component values used in the design are as follows:

- *R1=2.2 kΩ*
- *C1=0.1 μF*
- *R2=2.2 kΩ*
- *C2=0.1 μF*

The cutoff frequency for each stage is approximately equal, which ensures uniform filtering across both stages. This results in a smoother output waveform and improved noise reduction.



Note : The cascading technique effectively increases the order of the filter, thereby improving its frequency response.

Methodology

The design and simulation of the multi-stage RC low pass filter were carried out using the eSim EDA tool. The following steps were followed:

1. The RC low pass filter circuit was designed by selecting appropriate values of resistors and capacitors based on the required cutoff frequency.
2. Two RC stages were cascaded to form a multi-stage filter in order to improve the attenuation of high-frequency components.
3. The circuit schematic was created in the eSim environment by connecting resistors, capacitors, and input voltage source appropriately.
4. A sinusoidal input signal was applied using the voltage source with specified amplitude and frequency (sine(0 5 1k)).
5. The simulation was performed to observe the behavior of the circuit under the given input conditions.
6. Input and output waveforms were analyzed using the simulation results.
7. The output signal was compared with the input signal to evaluate the filtering performance and attenuation characteristics of the circuit.

Results and Analysis

The designed multi-stage RC low pass filter was simulated using the eSim tool with a sinusoidal input signal defined as sine(0 5 1k), having an amplitude of 5 V and a frequency of 1 kHz.

Input Signal:

The input waveform is a sinusoidal signal containing a frequency of 1 kHz. This signal serves as the test input to analyze the filtering behavior of the circuit.

Output Signal:

The output waveform is observed across the capacitor of the second stage. It is found that the amplitude of the output signal is significantly reduced compared to the input signal.

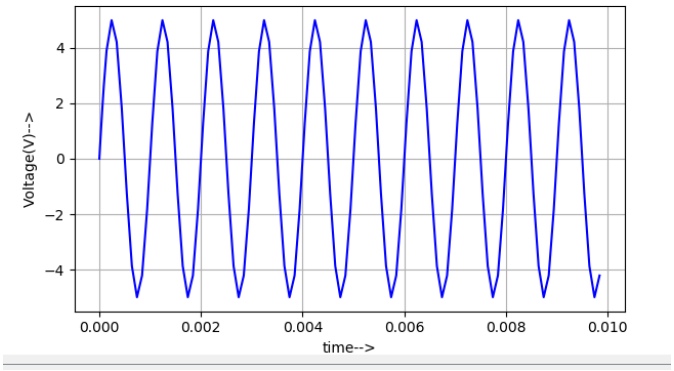
Analysis:

- The calculated cutoff frequency of the filter is approximately **723 Hz**.
- Since the input frequency (**1000 Hz**) is higher than the cutoff frequency, the signal undergoes attenuation.
- In the first RC stage, partial attenuation of the high-frequency component occurs.
- In the second stage, further attenuation takes place, resulting in a more reduced and smoother output signal.
- The cascading of two stages increases the overall attenuation and improves the filtering performance.

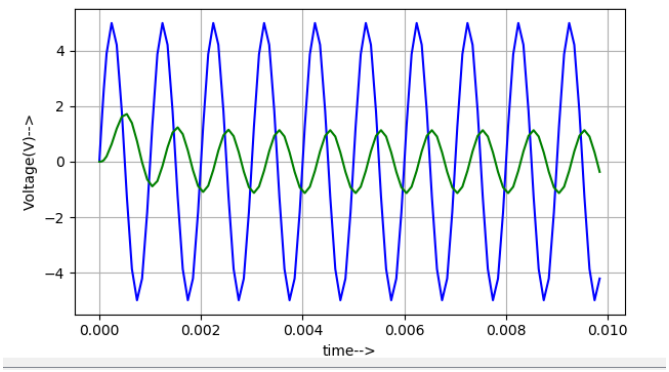
Observation:

- The output waveform has a lower amplitude compared to the input waveform.
- High-frequency components are effectively suppressed.
- The output signal appears smoother due to the filtering action of the capacitors.

Input Signal :



Input and Output :



Applications

The multi-stage RC low pass filter has a wide range of applications in electronic and communication systems, including:

1. Communication Systems:
   Used in systems such as OFDM to remove high-frequency noise and improve signal quality before processing or transmission.
2. Signal Conditioning:
   Helps in preparing signals by smoothing and filtering unwanted high-frequency components before further processing.
3. Audio Processing:
   Eliminates high-frequency noise in audio signals, resulting in clearer and smoother sound output.
4. Noise Reduction Circuits:
   Used in electronic circuits to suppress unwanted noise and interference.
5. Sensor Signal Filtering:
   Filters noisy signals from sensors to obtain stable and accurate readings.
6. Power Supply Filtering:
   Helps in reducing ripple and noise in power supply outputs

Conclusion

The project successfully demonstrates the design and simulation of a multi-stage RC low pass filter using the eSim EDA tool. The circuit was developed by cascading two RC filter stages to enhance the attenuation of high-frequency components.

The cutoff frequency of the filter was calculated to be approximately **723 Hz**, and a sinusoidal input signal of **1 kHz** was applied for analysis. Since the input frequency is higher

than the cutoff frequency, the output signal was attenuated, which confirms the correct functioning of the low pass filter.

The simulation results clearly show that the multi-stage configuration provides better filtering performance compared to a single-stage filter. The output waveform exhibits reduced amplitude and smoother characteristics due to effective suppression of high-frequency components.

Overall, the designed filter proves to be efficient for signal conditioning applications, and the approach of cascading RC stages can be effectively used in practical electronic and communication systems to improve signal quality.

Thus, the project validates the effectiveness of multi-stage RC filters in achieving enhanced frequency selectivity and improved signal integrity.

References :

1) Electronic tutorials on " Passive Low Pass Filter Design and Analysis".
2) FOSSEE Team, "eSim: Open Source EDA Tool."
   Available: https://esim.fossee.in
3) IEEE journals and conferences on Low Pass Filter Design Techniques.