Design and Analysis of an RC Low-Pass Filter for Noise Removal Using FFT Verification

Bhargav Krishnamurthy

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1 Introduction

In signal processing and electronic systems, noise removal is a fundamental requirement. A low-pass filter allows low-frequency components of a signal to pass while attenuating high-frequency noise. RC low-pass filters form the most basic analog filtering structure and are widely used in communication systems, control systems, and sensor signal conditioning. This project demonstrates the operation of an RC low-pass filter using simulation and frequency-domain verification. The ability of the RC circuit to suppress high-frequency noise while preserving the desired signal is demonstrated using transient and FFT analysis in LTspice and verified using Python.

2 Theory of RC Low-Pass Filter

The RC low-pass filter consists of a resistor and a capacitor connected in series, with the output taken across the capacitor.

2.1 Circuit Diagram

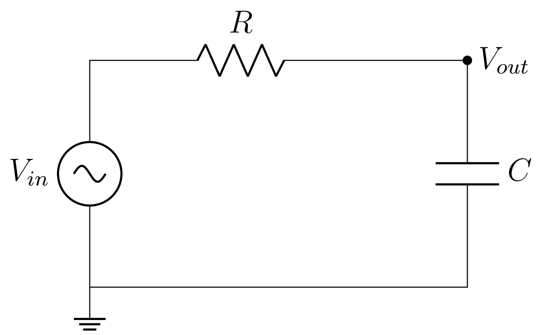

Figure 1: RC Low-Pass Filter Circuit

2.2 Circuit Description

- Resistor R is connected in series with the input.

- Capacitor C is connected from the output node to ground.
- Output voltage is measured across the capacitor.

2.3 Impedance Representation

The impedance of the components in the frequency domain is given by:

$$Z_R = R$$

$$Z_C = \frac{1}{j\omega C}$$

Using the voltage divider rule:

$$H(j\omega) = \frac{V_{out}}{V_{in}} = \frac{Z_C}{R + Z_C}$$

$$H(j\omega) = \frac{1}{1 + j\omega RC}$$

2.4 Magnitude Response

The magnitude of the transfer function is:

$$|H(j\omega)| = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

3 Derivation of Cutoff Frequency

The cutoff frequency is defined at the point where the output power becomes half of the input power. Since power is proportional to the square of voltage:

$$|H(j\omega)| = \frac{1}{\sqrt{2}}$$

$$\frac{1}{\sqrt{1 + (\omega RC)^2}} = \frac{1}{\sqrt{2}}$$

Squaring both sides:

$$1 + (\omega RC)^2 = 2$$

$$(\omega RC)^2 = 1$$

$$\omega = \frac{1}{RC}$$

Since $\omega = 2\pi f$:

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

4 Design Specifications

- Desired cutoff frequency: $f_c = 10$ Hz
- Signal frequency: 5 Hz
- Noise frequency: 50 Hz

4.1 Component Selection

$$RC = \frac{1}{2\pi f_c} = \frac{1}{2\pi \cdot 10} = 0.0159$$

Choosing:

$$R = 10k\Omega$$
$$C = \frac{0.0159}{10,000} \approx 1.6\mu F$$

Final selected values:

$$R = 10k\Omega, \quad C = 1.5\mu F$$

5 Input Signal Generation

A mixed-frequency test signal was applied in LTspice using a behavioral voltage source:

$$V(t) = \sin(2\pi \cdot 5t) + 0.8 \sin(2\pi \cdot 50t)$$

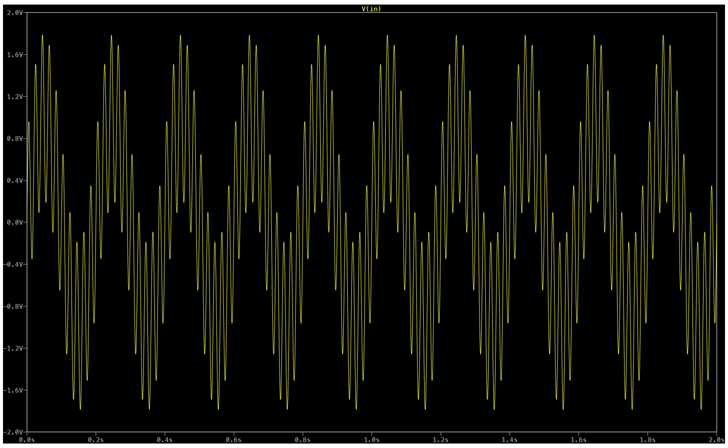

Figure 2: Input Signal

This represents a desired low-frequency signal corrupted by high-frequency noise.

6 Simulation Procedure

- The RC circuit was constructed in LTspice.
- The mixed signal was applied at the input.

- Transient analysis was performed using:

```
.tran 2
.save V(in) V(out)
```

7 FFT Verification Using Python

FFT analysis was performed on both input and output signals using scipy library in Python. The input FFT shows two dominant frequency components at 5 Hz and 50 Hz. After filtering, the 50 Hz component is significantly attenuated while the 5 Hz signal is preserved.

8 Results

- The RC filter effectively removes high-frequency noise.
- The low-frequency signal passes with minimal attenuation.
- The cutoff behavior matches theoretical predictions.
- A phase lag and slight time delay are introduced as expected.

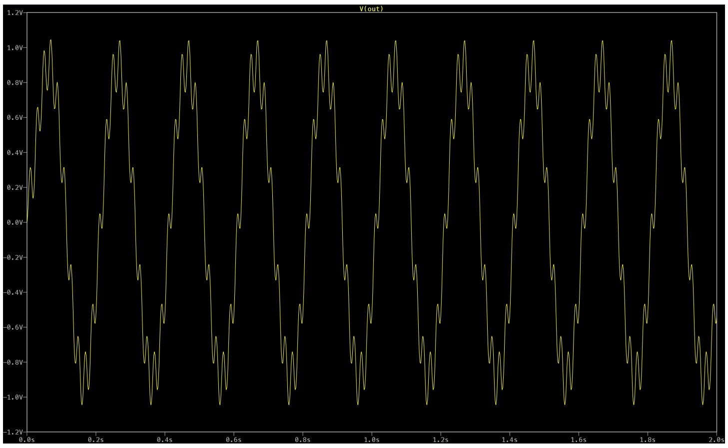

Figure 3: Output Signal

9 Conclusion

This project successfully demonstrates the design and verification of an RC low-pass filter for noise suppression. The mathematical derivation, component selection, transient simulation, and FFT-based frequency verification confirm the correct behavior of the filter.