RC Circuit Analysis: Transient Response, Frequency Domain, and Filter Design Laboratory Report

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Abstract

This laboratory report presents a comprehensive analysis of RC circuits, covering transient response characteristics, Laplace transform methods, frequency domain analysis, and filter design applications. Through computational analysis with Python, we demonstrate charging and discharging dynamics, time constant determination, Bode plot interpretation, and the design of low-pass, high-pass, and band-pass filter configurations. All numerical results are dynamically computed, ensuring reproducibility.

1 Introduction

RC circuits form the foundation of analog signal processing and filtering. The combination of resistance (R) and capacitance (C) creates a frequency-dependent impedance that enables selective signal attenuation and phase shifting.

Definition 1.1 (Time Constant)**.** *The time constant τ of an RC circuit is the time required for the voltage to reach approximately 63.2% of its final value during charging or decay to 36.8% during discharging:*

$$\tau = RC \tag{1}$$

2 Laplace Domain Analysis

The transfer function of an RC low-pass filter in the Laplace domain is:

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + sRC} = \frac{1}{1 + s\tau} \tag{2}$$

Theorem 2.1 (Voltage Equations via Laplace Transform)**.** *For a step input of magnitude V_0, the capacitor voltage during charging is:*

$$v_C(t) = V_0 \left(1 - e^{-t/\tau}\right) u(t) \tag{3}$$

where $u(t)$ is the unit step function.

Circuit Parameters:

- Resistance: $R =$ **??** Ω
- Capacitance: $C =$ **??** μF
- Time Constant: $\tau =$ **??** ms
- Cutoff Frequency: $f_c =$ **??** Hz

3 Transient Response Analysis

3.1 Charging and Discharging Dynamics

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Figure 1: Transient response characteristics: voltage, current, power, and energy.

Table 1: Charging Voltage at Key Time Constants

Time	**Voltage (V)**	**Percentage of V_0**
τ	**??**	63.2%
3τ	**??**	95.0%
5τ	**??**	99.3%

3.2 Pulse Response and Duty Cycle Effects

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Figure 2: Pulse response showing the effect of pulse period and duty cycle on output waveform.

4 Frequency Response Analysis

4.1 Bode Plot Characterization

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Figure 3: Frequency response characteristics: Bode plots, Nyquist diagram, and group delay.

Table 2: Frequency Response Characteristics

Parameter	**Value**	**Unit**
Cutoff Frequency	**??**	Hz
Magnitude at f_c	**??**	dB
Phase at f_c	**??**	degrees
Roll-off per Decade	**??**	dB
DC Group Delay	**??**	μs

5 Filter Design Applications

5.1 Low-Pass and High-Pass Configurations

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Figure 4: Filter configurations: low-pass and high-pass comparison with order effects.

5.2 Band-Pass Filter Design

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Figure 5: Band-pass filter design and frequency response analysis.

Table 3: Band-Pass Filter Parameters

Parameter	**Value**	**Unit**
Lower Cutoff f_L	??	Hz
Upper Cutoff f_H	??	Hz
Center Frequency f_0	??	Hz
Bandwidth	??	Hz
Quality Factor Q	??	–

6 Signal Processing Applications

6.1 Noise Filtering and Signal Conditioning

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Figure 6: Signal processing application: noise filtering with RC low-pass filter.

Signal Processing Results:

- SNR Before Filtering: **??** dB
- SNR After Filtering: **??** dB
- SNR Improvement: **??** dB

7 Component Sensitivity Analysis

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Figure 7: Component sensitivity analysis: tolerance and temperature effects.

Table 4: Sensitivity Analysis Summary

Parameter	**Value**	**Unit**
Nominal f_c	??	Hz
Std Dev (5% tolerance)	??	Hz
f_c Range (-40 to 85°C)	??	Hz

8 Conclusions

This laboratory analysis of RC circuits demonstrated:

1. **Transient Response**: The time constant $\tau =$ **??** ms governs charging/discharging dynamics, with the circuit reaching 99.3% of final value in 5τ.

2. **Frequency Response**: The first-order RC filter exhibits a cutoff frequency of $f_c =$ **??** Hz with -20 dB/decade roll-off and -45° phase shift at cutoff.

3. **Filter Design**: Low-pass, high-pass, and band-pass configurations were analyzed, showing how cascaded stages increase selectivity with -20n dB/decade roll-off for n stages.

4. **Signal Processing**: RC filtering improved SNR by **??** dB for the test signal with high-frequency noise.

5. **Sensitivity**: Component tolerances of 5% result in cutoff frequency standard deviation of **??** Hz, requiring careful component selection for precision applications.

The computational analysis ensures all results are reproducible and can be easily modified for different circuit parameters.