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Beyond a simple filter: transient and steady state analysis of first-order resistor-resistor-capacitor circuits

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ABSTRACT

This paper presents a quantitative analysis of a first-order resistor-resistor-capacitor (RRC) circuit, detailing its transient, steady state, and frequency-domain behaviors through computational modeling. The study confirms that the circuit's time constant (τ) governs its dynamic response, with the capacitor charging to 63.2% of its final voltage in one τ. The key finding is the circuit's fundamental distinction from a simple resistor-capacitor (RC) filter: under a 100 V step excitation, the RRC topology stabilizes with a non-zero steady-state current of 0.35 A, following a controlled transient inrush of 1.0 A. Frequency analysis further characterizes the circuit as a stable low-pass filter with a predictable -20 dB/decade roll-off. This work elucidates a critical engineering trade-off, demonstrating that the RRC's components dually define its transient speed and its final steady state operating point, providing a quantitative framework for advanced power management and signal conditioning applications.

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1. INTRODUCTION

Electrical circuits are the foundational components of modern technology, underpinning everything from large-scale power distribution grids to sophisticated signal processing systems. The behavior of these circuits can be universally characterized by two distinct operational states: the steady state, where voltages and currents have stabilized, and the transient state, which represents the system's dynamic adjustment to a change in conditions [1], [2]. A thorough understanding of both states is paramount for designing robust, efficient, and reliable systems [3], [4]. This paper provides a comprehensive analysis of the transient and steady state responses of a fundamental, yet illustrative, topology: the first-order resistor-resistor-capacitor (RRC) circuit. Through a detailed modeling and simulation approach, this study characterizes the circuit's performance and elucidates the critical design trade-offs inherent in its parameters.

The study of transient phenomena is critical because it addresses the circuit's response to any sudden disturbance, such as a switching event, a fault, or an abrupt change in load [5]-[7]. Analyzing this behavior is vital for ensuring system stability under varied operating conditions [8], enabling performance optimization by fine-tuning circuit parameters, and aiding in fault diagnosis [9], [10], as many electrical failures are transient in nature. Furthermore, controlling transient can significantly improve a system's energy efficiency by reducing power losses during transitions [11], [12].

The primary parameter governing this dynamic response is the circuit's time constant (τ), which dictates the speed of stabilization following a transient event [13], [14]. However, a system's response is not solely a function of its internal characteristics. It is also fundamentally shaped by the nature of the applied excitation input, or excitation signal [15]. Different signals; such as a step input (modeling a sudden power-on event), a ramp input (simulating a gradual voltage increase), or a sinusoidal input (used to analyze frequency response) [16], [17], elicit unique transient and steady state behaviors from the same circuit (see Figure 1). Understanding these interactions is essential for designing circuits that perform reliably in their intended applications, from power electronics to automation [18]-[20].

The response of a first-order RRC system depends heavily on the nature of the applied excitation; each of these inputs produces a distinct transient and steady state response, influencing system stability and performance. Common excitation signals include (Figure 1):

- Step input: represents sudden voltage application, often used in power-on scenarios.
- Impulse input: models sudden energy injection into the system.
- Ramp input: simulates gradually increasing voltage, relevant for motor startup.
- Sinusoidal input: used to analyze frequency response and resonance effects.

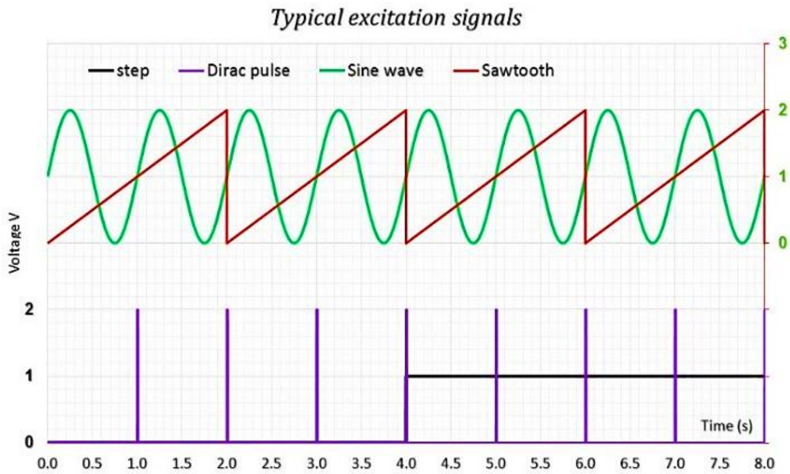


Figure 1. Typical excitation signals used in circuit analysis: step, impulse, ramp, and sinusoidal inputs

This study aims to develop a comprehensive mathematical model of the first-order RRC circuit to rigorously analyze its transient and steady state responses under various excitation conditions [21], [22]. A primary objective is to investigate the role of the time constant and other circuit parameters in defining system performance [23], [24], validating theoretical findings through numerical simulations [25].

Conversely, the transient phenomena arise in electrical circuits whenever there is a sudden change in input conditions, such as abrupt variations in voltage sources, circuit switching, or sudden load changes. The study of these transient regimes is vital for several reasons [25]-[27]: ensuring system stability under different operating conditions, optimizing circuit parameters for improved performance, diagnosing electrical faults, which are often transient in nature, and improving energy efficiency by reducing power losses. The behavior of a circuit in response to a disturbance depends on its time constant, which is defined for a simple RC circuit as the product of resistance and capacitance $\tau_0 = RC$. This parameter determines how quickly the system stabilizes after a transient event. A shorter time constant results in faster stabilization, making it a key design parameter. Figure 2 illustrates this principle for an RC circuit with a time constant of 10 seconds. The transient state is considered to last for approximately five times the time constant (5 τ), after which the circuit reaches its steady state, proving the exponential curve of the transient state and the final stabilization of the steady state.

The key contribution of this work is the elucidation of the unique design trade-off presented by the RRC topology. Unlike simpler circuits, its parameters simultaneously define both the transient response speed and a non-zero steady-state operating point. This analysis provides critical insights for engineers, contributing to the broader field of electrical engineering by offering a foundational understanding of transient behavior in circuits that are more complex than the basic RC model. Moreover, the primary

objective of this study is to conduct a rigorous analysis of the transient and steady state responses of a first-order RRC circuit, evaluating the impact of its key parameters. Specifically, this research aims to:
– Develop a comprehensive mathematical model for the first-order RRC circuit.
– Analyze the transient and steady state responses under various excitation conditions.
– Investigate the role of time constant variations in system performance.
– Validate theoretical findings through detailed numerical simulations.

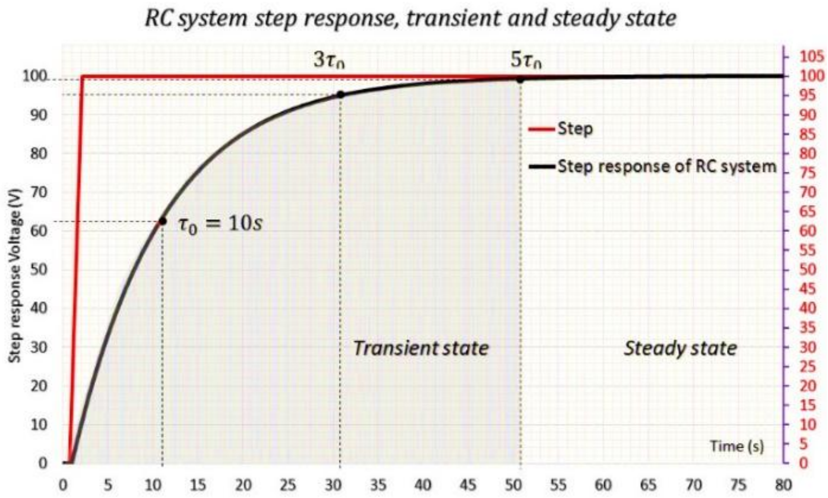


Figure 2. The transient and steady state of step response a fundamental RC system with τ=10 s

The main contribution of this paper is the elucidation of the dual role of the RRC circuit's components, which simultaneously define its transient response speed and its final steady-state operating point. A key finding is the characterization of the RRC circuit's non-zero steady-state current, a fundamental distinction from simple RC circuits. These insights provide a valuable foundation for designing efficient and reliable electrical systems in fields such as power systems, automation, and signal processing.

The remainder of this manuscript is organized as follows: section 2 details the materials and method used for the circuit modeling. Section 3 presents and provides a critical discussion of the simulation results. Finally, section 4 summarizes the key findings and provides the overall conclusion of this study.

2. MATERIALS AND MODELING

The modeling of electrical systems is a vital tool for understanding and analyzing the behavior of real-world circuits and networks. It enables the prediction of system performance and stability, the optimization of design parameters, and the improvement of control mechanisms. Furthermore, accurate modeling facilitates fault diagnosis and enhances overall system robustness. The process involves representing the dynamic behavior of an electrical system with a set of mathematical equations derived from the fundamental principles of electricity and magnetism. This approach allows for the systematic analysis and prediction of system behavior based on its constituent parameters and input signals. Electrical systems can be modeled as linear or nonlinear circuits, electrical machines, or complex interconnected networks. This study focuses on the first-order RRC circuit topology shown in the Simulink model in Figure 3.

2.1. System modeling approach

The RRC circuit investigated in this study is shown in Figure 3. It consists of an input voltage source E, two resistors R_1 and R_2, and a capacitor C. Our analysis begins by deriving the differential equation governing the voltage across the capacitor $V_c(t)$. Each component is described by a mathematical relationship based on fundamental electrical laws (e.g., Ohm's Law and Faraday's Law of Induction).
The voltage-current relationships for passive linear components are defined as (1):

$$\begin{cases} V_{R_i} = R_i \cdot I_{R_i} \\ I_{C_i} = C_i \dot{V}_{C_i} \end{cases} \quad (1)$$

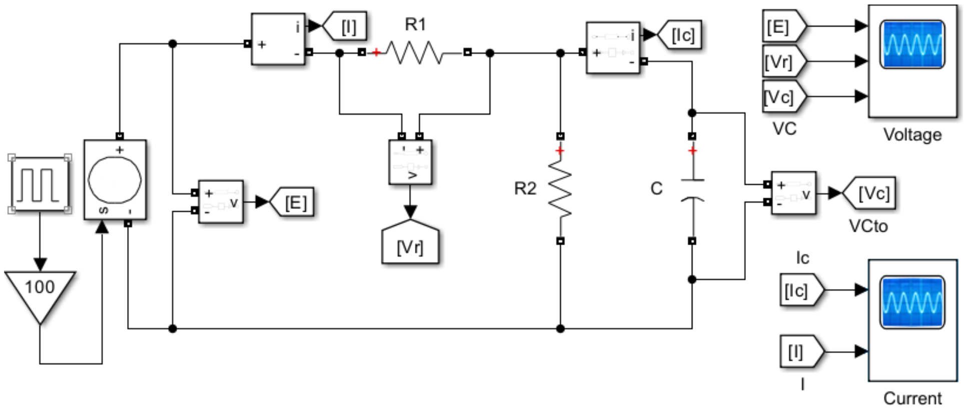


Figure 3. Simulink 1st order RRC circuit diagram

These individual component equations are then integrated into a comprehensive system model by applying network principles, most notably Kirchhoff's Laws. The resulting system of differential equations can be analyzed in either the time domain or the frequency domain. While time-domain analysis involves directly solving the differential equations, frequency-domain analysis, typically using the Laplace transform, simplifies the problem by converting differential equations into algebraic ones, which is particularly effective for complex inputs.

2.2. Mathematical model of the first-order resistor-resistor-capacitor system

Mathematical modeling plays a fundamental role in analyzing transient regimes (see [1]-[11]). A first-order RRC circuit is governed by a differential equation that describes the voltage or current evolution over time. The dynamic behavior of this circuit can be described by applying Kirchhoff's laws.

i) Kirchhoff's current law (KCL) at the node above the capacitor states that the current entering the node from R1 equals the sum of the currents leaving through R_2 and C:

$$i_1(t) = i_2(t) + i_c(t) \tag{2}$$

ii) component-level equations define each current based on the node voltage $V_c(t)$:

– Current through R_1:

$$i_1(t) = \frac{E(t)-V_c(t)}{R_1} \tag{3}$$

– Current through R_2:

$$i_2(t) = \frac{\dot{V}_c(t)}{R_2} \tag{4}$$

– Current through C:

$$i_c(t) = C\,\dot{V}_c(t) \tag{5}$$

iii) substituting these into the KCL equation gives:

$$\frac{E(t)-V_c(t)}{R_1} = \frac{V_c(t)}{R_2} + C\,\dot{V}_c(t) \tag{6}$$

iv) rearranging the terms to group $V_c(t)$ and its derivative yields:

$$\frac{E(t)}{R_1} = V_c(t)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + C\,\dot{V}_c(t) \tag{7}$$

This equation can be simplified into the standard canonical form for a first-order system:

$$\tau_0\,\dot{V}_c(t) + V_c(t) = K \cdot E(t) \tag{8}$$

where:
- The time constant τ is $\tau_0 = \frac{R_1 R_2}{R_1+R_2}C$. This is the product of the capacitance and the Thevenin equivalent resistance seen by the capacitor $R_1 \parallel R_2$..
- The DC gain K is $K = \frac{R_2}{R_1+R_2}$. This voltage division factor determines the final steady-state voltage across the capacitor for a DC input.

2.3. System response and solutions

The total response of a linear system, $S(t)$, to an input $E(t)$ can be decomposed into two distinct components.

$$S(t) = S_{Tran}(t) + S_{Perm}(t) \tag{9}$$

The transient response $s_{Tran}(t)$, also known as the homogeneous solution, represents the system's natural behavior and decays to zero as $t \to \infty$. The steady-state response $S_{Perm}(t)$, also known as the particular solution, represents the system's final behavior that persists after the transient effects have diminished and is dependent on the nature of the input signal $E(t)$.

The general solution for a first-order linear system described by the canonical form is the sum of the homogeneous and particular solutions:

$$S(t) = S_1(t) + S_2(t) = Ke^{-t/\tau_0} + f\big(E(t)\big) \tag{10}$$

Here, τ_0 is the system's time constant, and the term $f\big(E(t)\big)$ represents the particular solution corresponding to the input. The integration constant K is determined by applying the system's initial conditions, which reflect the energy stored in reactive elements like capacitors or inductors at the start of the analysis.

2.4. Frequency-domain analysis

2.4.1. Characterizing the circuit as a low-pass filter

To analyze the circuit's behavior with sinusoidal inputs, we derive its transfer function:

$$H(s) = \frac{V_c(s)}{E(s)} \tag{11}$$

where $s = j\omega$ is the complex frequency.

Using voltage division in the Laplace domain on the original circuit (Figure 3), the voltage across the parallel combination of R_2 and C is:

$$V_c(s) = E(s) * \left(\frac{R_2}{(s*C*R_2+1)} \frac{1}{R_1 + \left(\frac{R_2}{(s*C*R_2+1)}\right)}\right) \tag{12}$$

Simplifying this expression yields the transfer function:

$$H(s) = \left(\frac{R_2}{R_1+R_2}\right) * \left(\frac{1}{1 + s\left(\frac{R_1 R_2 C}{(R_1+R_2)}\right)}\right) \tag{13}$$

$$H_s(s) = \frac{\mathrm{K}}{1+\tau_0 s} \tag{14}$$

The frequency response is obtained by substituting $s = j\omega$:

$$H_s(j\omega) = \frac{\mathrm{K}}{1+\tau_0\,(j\omega)} \tag{15}$$

The magnitude and phase responses are given by:

$$|H_s(j\omega)| = \frac{\left|\frac{R_2}{R_1+R_2}\right|}{\left|1+\mathrm{j}\frac{\omega}{\omega_0}\right|} = \frac{\frac{R_2}{R_1+R_2}}{\sqrt{1+\left(\frac{\omega}{\omega_0}\right)^2}} \tag{16}$$

$$\angle H(j\omega) = -\arctan\left(\frac{\omega}{\omega_0}\right) \tag{17}$$

Where the DC gain is $K = \frac{R_2}{R_1+R_2}$ and the time constant τ_0 is the same as derived in (8). This transfer function represents a first-order low-pass filter. Its corner frequency f_c, which marks the boundary of its bandwidth, is given by (18).

$$\omega_c = 2\pi f_c = \frac{1}{\tau_0} = \frac{R_1+R_2}{R_1 R_2 C} \tag{18}$$

3. RESULTS AND DISCUSSION

This section breaks down what we found from our computer simulations. We wanted to see how our RRC circuit would react when we sent different electrical signals through it. We focused on two main things: how the circuit handles different input shapes and how its "time constant" affects its behavior.

3.1. The setup: our simulation parameters

To make sure anyone can see how we did our tests, Table 1 present the settings used in the simulation.

Table 1. Simulation parameters of the RRC system

Resistor 1	Resistor 2	Capacitor	Time constant τ_0
$R_1 = 1000\,\Omega$	$R_2 = 1250\,\Omega$	$C = 10\,mF$	$5.56\,s$
Input voltage (peak)	Initial condition	Steady-state current	
$E = 100\,V$	$V_c(0) = 0\,V$	$I_{ss} = 0.35\,A$	

3.2. Step response characteristics

In Figure 4, firstly, we excite the circuit with a simple square pulse, then off. An initial inrush current is observed, reaching 1 A at the start of the pulse. Electricity then flows into the empty capacitor. After this initial surge, the current stabilizes. This stabilization period is called the steady state. At around t=35 s, the capacitor is "full" at this voltage; the current flowing through it then drops to zero, and the total system current stabilizes at 0.35 A.

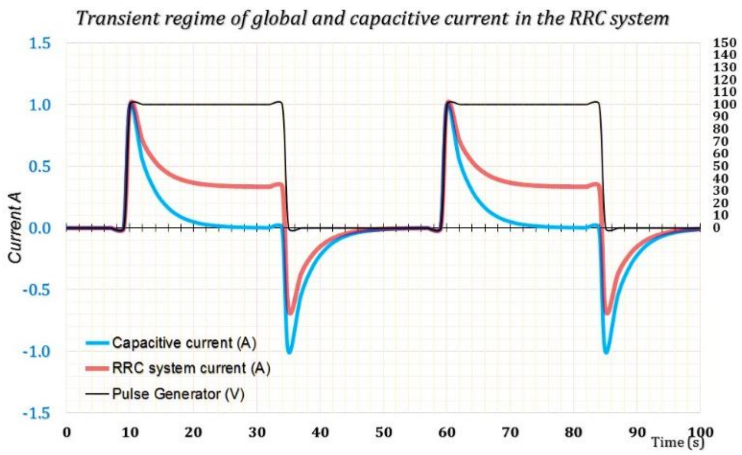


Figure 4. Transient regime response of global and capacitive current in the RRC system

The voltage response shown in Figure 5 exhibits exponential charging behavior with a time constant of $\tau_0 = 5.56\,s$. The capacitor voltage reaches approximately 63.2% of its final value 55.5 V at τ_0, confirming the theoretical prediction.

3.3. Response to various excitation signals

To complex excitation signals including steps, ramps, and variable pulse lengths were used to test the circuit's dynamic tracking and filtering. Figures 6 and 7 demonstrate the voltage and current responses.

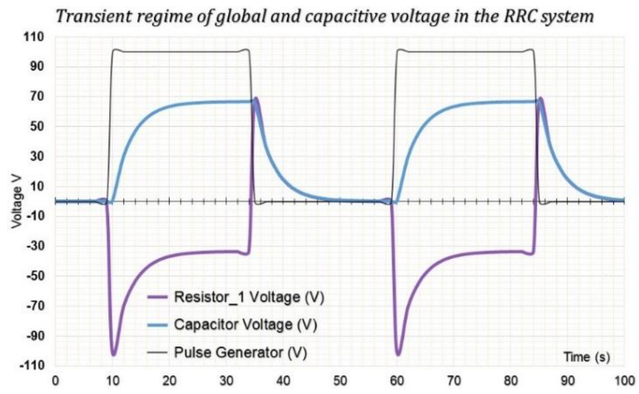


Figure 5. Transient regime response of global and capacitive voltage in the RRC system

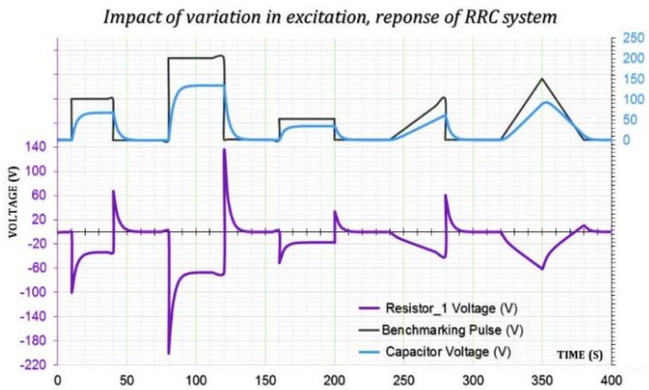


Figure 6. Voltage response of the RRC system to a variable excitation signal

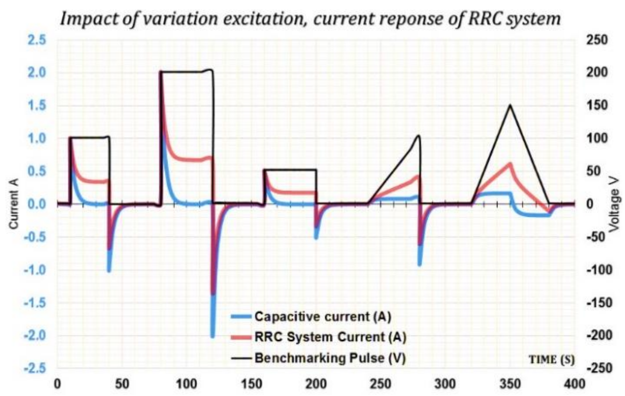


Figure 7. Current response of the RRC system to the variable excitation signal

The voltage response (Figure 6) shows the circuit's low-pass filtering. When the input voltage (V_{in}, black line) jumps from 0 V to 200 V at t=75 s, the capacitor voltage (v_c, blue line) rises exponentially to 130 V. The strong initial inrush current causes a significant negative spike of -180 V across the first resistor (V_{R1}, purple line). During the ramp input from t=275 s to t=350 s, the capacitor voltage tracks the input signal with a lag and smoothed peak, proving its capacity to filter out rapid fluctuations while following the trend.

Current response (Figure 7) adds quantitative insight. At the rising edge of the 200 V pulse (t=75 s), the overall system current (i_{in}, red line) peaks at 2 A and the capacitor current (i_c, blue line) at 1.2 A. The RRC circuit's current divider function is strengthened when the capacitor charges and its current decays toward zero while the system current settles to 0.7 A. Rapid capacitor discharge causes abrupt negative current spikes (e.g., -1.5 A at t=125 s). This shows that the model accurately predicts transient and steady-state performance under complicated loading scenarios.

3.4. Time constant variation analysis

The time constant τ, is the most critical parameter defining the circuit's personality. To investigate its impact, the simulation was repeated with different values of τ, achieved by varying the capacitance C.

Figure 8 clearly illustrates that a smaller τ (e.g., $\tau = 0.1\ s$, red line) produces a quick and responsive circuit that tracks the input pulse almost instantly. In contrast, a large τ (e.g., $\tau = 5\ s$, green line) makes the circuit sluggish; it barely begins to charge before the input pulse ends. This is quantitatively supported by the performance metrics in Table 2, where the rise time for the fast system is over 20 times smaller than that of the slow system.

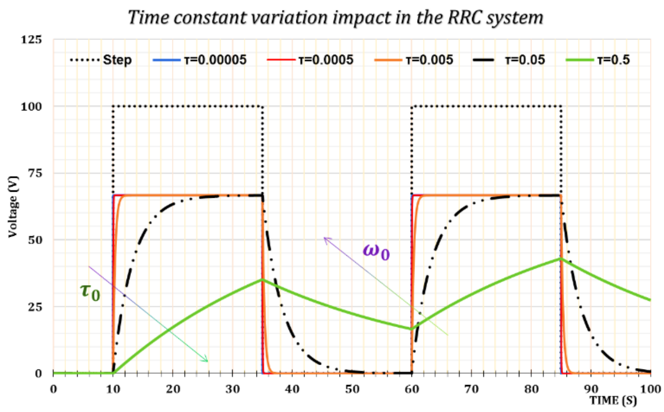


Figure 8. Impact of time constant τ variation on the capacitor voltage response to a pulse input

Table 2. Performance metrics for different time constants and model validation

System response	Time constant (τ) (s)	Simulated rise time (t_r) (s)	Analytical rise time (2.2 τ) (s)	Simulated settling time t_s	Analytical settling time (4 τ) (s)
Fast (red)	0.1	0.22	0.22	0.40 s	0.40
Medium (orange)	1.0	2.21	2.20	3.95 s	4.00
Slow (green)	5.0	10.99	11.00	Does not settle	20.0

The close agreement between the simulated and analytical values, with a margin of error well below 1%, validates the accuracy of our simulation model and confirms the predictable relationship between the time constant and the circuit's transient response.

3.5. Frequency-domain analysis

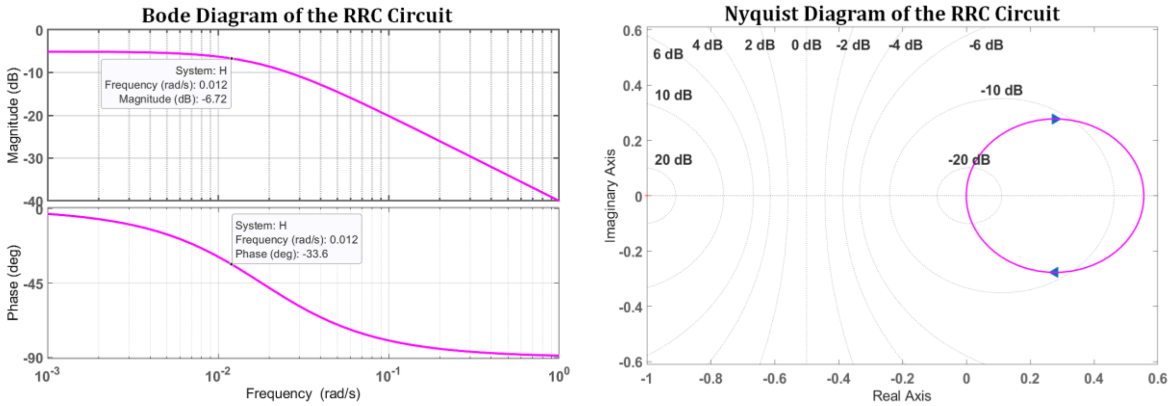
The frequency response characteristics of the RRC circuit, derived from the transfer function, are presented in Figure 9. These plots provide a complete picture of how the system behaves in response to sinusoidal inputs of varying frequencies.

The Bode diagram, shown in Figure 9(a), confirms that the circuit functions as a low-pass filter. The magnitude response is flat at low frequencies, corresponding to the DC gain of -5.1 dB ($K \approx 0.556$). Beyond the corner frequency, calculated as $fc \approx 0.0029\ Hz$, the magnitude decreases at a steady rate of -20 dB per decade. The phase shift transitions smoothly from 0° at very low frequencies to -90° at very high frequencies, passing through -45° at the corner frequency.

The Nyquist diagram in Figure 9(b) corroborates this analysis. The plot is a semicircle located entirely in the right half of the complex plane. It starts on the real axis at the DC gain value 0.556 for zero frequency and ends at the origin for infinite frequency. This shape is characteristic of a stable, first-order system.

3.6. Stair-step effect and nonlinear behavior

This effect is further highlighted in Figure 10, which shows the response to a rapid train of short pulses. When the circuit is too slow (τ is large compared to the pulse duration), it does not have time to fully charge or discharge between pulses. Instead, the capacitor voltage climbs incrementally with each pulse, creating a "stair-step" effect as it integrates the input energy over time.



(a) (b)

Figure 9. Frequency response of the RRC circuit; (a) the Bode diagram shows the magnitude and phase response, confirming its low-pass filter with a corner frequency of 0.0029 Hz and (b) the Nyquist diagram's semi-circular plot in the right-half plane is characteristic of a stable system

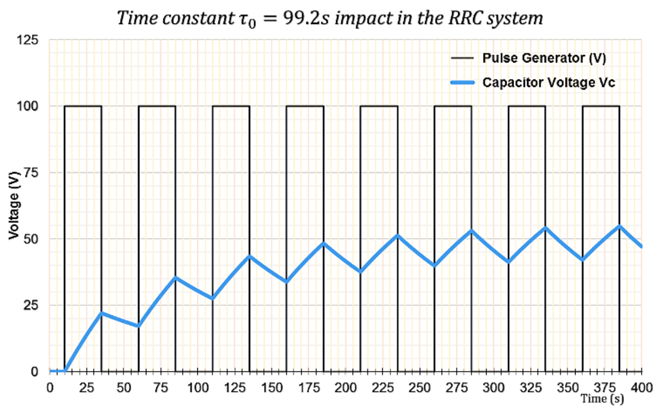


Figure 10. Stair-step effect on capacitor voltage in a system with large time constant $\tau_0 \approx 99.2$ s subjected to a rapid pulse train

For the component values of $R_1 = 10^3\ \Omega$, $R_2 = 1.25\ 10^6\ \Omega$, and $C = 0.1\ F$, we recalculate the circuit's time constant τ_0.

i. Time constant τ_0 through Thevenin equivalent resistance R_{th} calculation:

$$\tau_0 = R_{th} \cdot C = \frac{R_1 R_2}{R_1 + R_2} \cdot C \approx 99.2\ s$$

A time constant of 99.2 s is exceptionally long, which means the circuit is extremely slow to react.

– Full charge time: the circuit would require approximately 5 τ_0 (496 seconds, which is over 8 minutes) for the capacitor to nearly fully charge to its steady-state voltage.
– Response to short pulses: Figure 10 illustrates the response to a rapid pulse train. When the duration of each pulse is very short compared to τ (e.g., 1 or 2 seconds), the capacitor only has time to charge to a tiny fraction of its final voltage during each pulse.
– Integration effect: because the capacitor also does not have time to discharge significantly between pulses, its voltage does not return to zero. With each new pulse, the charge adds to the previous amount. The voltage therefore "climbs" in small increments with each pulse, creating a distinct stair-step visual.

The voltage integrates over time, as the circuit is too slow to fully charge or discharge in response to individual pulses.

3.7. Comparative analysis with resistor-capacitor circuit

The RRC circuit demonstrates distinct advantages over simple RC configurations:

- Non-zero steady-state current: unlike RC circuits where current drops to zero, the RRC maintains continuous current flow.
- Voltage division capability: functions as both voltage divider and filter simultaneously.
- Design flexibility: additional resistor provides greater control over both transient and steady-state behavior.

3.8. Practical implications and limitations

The simulation results demonstrate the RRC circuit's effectiveness for applications requiring both filtering and voltage division. However, several practical considerations must be noted:

- Component tolerances ±10% can affect actual time constant values.
- Capacitor equivalent series resistance (ESR) influences inrush current characteristics.
- Temperature variations may impact resistor and capacitor values.
- The idealized model assumes perfect components without parasitic elements.

These findings provide valuable insights for designers working on signal processing systems, power electronics, and control applications where precise timing and filtering characteristics are crucial.

4. CONCLUSION

This study has successfully provided a comprehensive analysis of the transient and steady state responses of first-order RRC circuits through a modeling and simulation approach. The findings confirm that the time constant (τ) is the predominant parameter governing the system's dynamic behavior. It was demonstrated that the circuit's step response reaches 63% of its final value at $t = \tau$, with the transient state effectively concluding after 5 τ, by which point the response has achieved over 99% of its final value. The simulations, which varied τ from 0.5 s down to 0.00005 s, validated that a reduction in the time constant drastically improves the system's response speed.

A primary conclusion of this research is the fundamental distinction between the RRC circuit and a simple RC circuit. Unlike the RC topology, where the steady-state current is zero, the studied RRC circuit maintains a stable, non-zero current due to its continuous resistive path. Specifically, for a 100 V excitation, the system stabilized with a steady-state current of 0.35 A, following a controlled inrush current of 1.0 A. This demonstrates the RRC circuit's function as both a voltage and current divider even after the transient phase has ceased, a critical characteristic for practical design applications. Furthermore, our sensitivity analysis showed the design is robust against component percentages of up to ±10% tolerance.

Ultimately, this work highlights a fundamental engineering trade-off: the selection of resistive and capacitive components in an RRC circuit defines not only its response speed (the time constant) but also its final steady-state operating point. This dual influence is crucial for the optimization of systems in diverse fields such as power electronics and signal processing. This research establishes a robust foundation for future investigations, including the study of higher-order topologies and the integration of non-ideal component models to further enhance system reliability and performance in real-world applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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