

Unveiling Hidden Dynamics: An Experimental Quantification of Non-Ideal Capacitor Behavior in First-Order RC Transient Circuits for Enhanced Pedagogy in Basic Electronics

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Abstract: *Background:* First-order Resistor–Capacitor (RC) transient analysis is a cornerstone of basic electronics engineering education. Textbooks and laboratory manuals universally assume an ideal capacitor, predicting a perfect exponential charge and discharge governed by a single time constant $\tau = RC$. In practice, students frequently observe deviations—incomplete discharge, residual voltage, and unexpectedly long settling tails—that cannot be explained by the ideal model. These anomalies, rooted in parasitic effects such as dielectric absorption, equivalent series resistance (ESR), and leakage, are rarely addressed in introductory curricula, leaving a critical gap between theory and measurement.

Objective: This work provides a systematic, quantitative investigation of non-ideal capacitor behavior in a standard first-order RC step-response experiment. Five widely available capacitor technologies—aluminum electrolytic, tantalum, polyester film, X7R ceramic, and C0G/NP0 ceramic—are evaluated under identical electrical conditions. The study aims to (1) measure the magnitude of deviation from the ideal exponential response, (2) identify the dominant parasitic mechanism, and (3) propose a practical, dual-time-constant model that reconciles observations with theory without overwhelming beginners.

Methods: A single-shot discharge from 5 V to 0 V is applied after a 60 s pre-charge to saturate dielectric absorption. The series resistor $R = 1.000 \text{ k}\Omega$ is used with nominal $C = 10.0 \text{ }\mu\text{F}$, giving an ideal time constant of 10 ms. The capacitor voltage is recorded for 50 ms (5τ) using a high-impedance differential oscilloscope probe. For each capacitor type, the transient is averaged over 20 shots and fitted to both a single-exponential and a dual-exponential model derived from a Debye-type dielectric absorption equivalent circuit. Residual voltage at $t = 50 \text{ ms}$, ESR from the initial voltage step, and effective time constants are extracted.

Results: Dielectric absorption is the dominant non-ideality. Aluminum electrolytic capacitors exhibited a residual voltage of 2.5 % of V_{DD} and a slow-mode time constant of 500 ms—fifty times the main time constant. X7R ceramics showed a 2.6 % residual and a time constant of 600 ms, with strong voltage dependence. Polyester film and C0G capacitors showed residuals of 0.70 % and 0.68 %, essentially matching the ideal 0.67 % value. The dual-exponential model reduced the root-mean-square error (RMSE) of the fit by a factor of 7 to 10 compared to the single-exponential model for high-absorption dielectrics.

Conclusion: Capacitor parasitics, particularly dielectric absorption, produce measurable and pedagogically significant distortions in basic RC transient experiments. A simple two-branch equivalent circuit, requiring only one additional resistor and capacitor, captures the observed behavior with high fidelity and can be seamlessly introduced in undergraduate laboratories. Recommendations are given for component selection and instructional design, empowering students to connect ideal theory with physical reality.



Keywords: RC circuit, dielectric absorption, capacitor parasitics, transient response, dual-time-constant model, basic electronics education

I. INTRODUCTION

The step response of a first-order RC network is one of the first dynamic systems an electronics engineering student encounters. The exponential functions $v_C(t) = V_0 (1 - e^{-t/\tau})$ (charging) and $v_C(t) = V_0 e^{-t/\tau}$ (discharging) with $\tau = RC$ are derived from the ideal capacitor constitutive relation $i = C \, dv/dt$, assuming no parasitic elements [1,2]. This idealization is mathematically elegant and provides an excellent entry point into time-domain circuit analysis. However, when students build the circuit on a breadboard using real components and observe the waveform on an oscilloscope, they often note puzzling discrepancies: the capacitor voltage never quite reaches the supply rail during charge, a small offset remains after a supposedly complete discharge, and the waveform occasionally drifts over successive cycles.

Experienced educators recognize these effects as manifestations of capacitor non-idealities—ESR, leakage current, and dielectric absorption (also called dielectric relaxation or soakage) [3,4]. While these topics are covered in specialized courses on component engineering or precision analog design, they are almost entirely omitted from basic electronics syllabi. As a result, students either ignore the discrepancies, lose confidence in the theory, or develop misconceptions. The literature on dielectric absorption is rich, with models ranging from the classical Debye relaxation [5] to distributed-element representations (Cole–Cole, Davidson–Cole) [6], but these are often mathematically advanced. A practical, experimentally grounded treatment suitable for introductory laboratories remains absent.

This paper bridges the gap. Through a carefully controlled set of measurements on five representative 10 μF capacitors, we quantify the departure from ideality, identify dielectric absorption as the primary culprit, and propose an accessible dual-time-constant model that extends the standard RC analysis by a single additional branch. The experimental design intentionally uses equipment found in a typical undergraduate lab—a DC power supply, a fast switch, a digital storage oscilloscope, a 1 k Ω resistor, and a handful of capacitors—so that the work can be readily replicated or adopted as a laboratory module. With extensive experience in both teaching and research in basic electronics, the authors have distilled the essential physical insights into a rigorous yet comprehensible study that highlights the true behavior of the humble capacitor.

II. BACKGROUND AND THEORY

2.1 Ideal First Order RC Transient

Consider a series circuit consisting of a resistor R and a capacitor C , driven by a voltage source $v_{\text{in}}(t)$ that steps from 0 to V_0 at $t = 0$. The governing differential equation is:

$$RC \frac{dv_C}{dt} + v_C = v_{\text{in}}(t) \quad \text{(1)}$$

For an initially discharged capacitor, the solution for the charging phase is

$$v_C(t) = V_0 \left(1 - e^{-t/RC}\right) \quad \text{(2)}$$

After the capacitor reaches V_0 , the source is switched to 0 V (discharge), yielding

$$v_C(t) = V_0 e^{-t/RC} \quad \text{(3)}$$

The time constant $\tau = RC$ fully characterizes the dynamics. The voltage reaches 63.2 % of its final value after one time constant, and after 5τ it is within 0.67 % of the steady state.

2.2 Real Capacitor Model

A real capacitor exhibits a more complex impedance due to construction, materials, and packaging. The classical equivalent circuit that captures the dominant low-frequency and transient anomalies is shown in Fig. 1. It comprises:

& C_0 : the main, ideal capacitance.

& R_{ESR} : equivalent series resistance (leads, foils, electrolyte).

& R_{leak} : parallel leakage resistance (typically hundreds of M Ω to G Ω , representing dielectric finite resistivity).



& A dielectric absorption branch: a series combination R_{da} and C_{da} in parallel with C_0 . This branch accounts for the slow polarization mechanisms within the dielectric [3,4].

Fig. 1 Real capacitor model including ESR, leakage, and dielectric absorption branch (parallel combination of C_0 , series $R_{\text{da}}C_{\text{da}}$, and R_{leak} , all in series with R_{ESR}).

For a step response, R_{ESR} introduces an initial voltage jump at the moment of switching. Leakage causes a slow drift toward a resistive-divider equilibrium. Dielectric absorption produces a fast initial transient governed by C_0 , followed by a much slower redistribution of charge between C_0 and the absorption branch. During discharge, the absorption branch slowly releases trapped charge, preventing the terminal voltage from reaching zero within the conventional 5τ observation window.

2.3 Dual Time Constant Approximation

To keep the analysis accessible, we neglect R_{ESR} during the slow transient (its effect ceases within microseconds for large capacitors) and absorb leakage into a slightly modified final value. After a long pre-charge that fully polarises both C_0 and C_{da} to V_0 , the discharge voltage across the parallel combination can be described by a sum of two exponentials [4]:

$$v_C(t) \approx V_0 \left(k_1 e^{-t/\tau_1} + k_2 e^{-t/\tau_2} \right), \quad (4)$$

where τ_1 is close to $R C_0$, $\tau_2 \approx R_{\text{da}} C_{\text{da}}$, and $k_1 + k_2 = 1$. The ratio k_2/k_1 is related to the dielectric absorption coefficient, usually expressed as a percentage.

III. EXPERIMENTAL METHODOLOGY

3.1 Component Selection

Five capacitor types, all with a nominal capacitance of $10.0 \mu\text{F}$ and rated voltage $\geq 25 \text{ V}$, were sourced from reputable manufacturers (Table I). A $1.000 \text{ k}\Omega$ metal-film resistor (tolerance $\pm 0.1 \%$, temperature coefficient $\pm 15 \text{ ppm}/^\circ \text{C}$) served as the circuit resistance. The actual capacitance and ESR of each sample were verified using an LCR meter (Keysight E4980A) at 1 kHz prior to the transient test.

TABLE I CAPACITOR SAMPLES

ID	Type	Part Example	Nominal C (μF)	Measured C (μF)	Measured ESR @ 1 kHz (Ω)
A	Aluminu				

