Low-Cost Return-Voltage Measurement of Dielectric Absorption in a Multilayer Plasticized-PVC Capacitor with a Quantified Instrument Bound

Ashrith Reddy Aleti and JSSG Srinivas Rao

***Abstract*—Return-voltage measurement (RVM) has proved useful for characterizing slow polarization in insulating dielectrics, but normally requires a laboratory electrometer. In this work, an RVM front end was assembled using a single, commercially available, off-the-shelf CMOS operational amplifier (with a typical input bias current of 10 fA) and a handheld multimeter, then applied to a multilayer capacitor made of ordinary plasticized poly(vinyl chloride) (PVC) with a capacitance of 14.75 nF. The results showed that the open-circuit voltage, following poling at 9.56 V for anywhere from 60 to 1800 seconds and a 10-second short circuit, reached a maximum, $V_{\max}$ at time $t_{\max}$, before decaying. $V_{\max}$ increased from 0.584 ± 0.009 V to 1.295 ± 0.008 V with increasing poling time (run-to-run standard deviation $\leq$1.5%), while $t_{\max}$ was delayed (from 48 ± 5 s to 66 ± 5 s) and the subsequent voltage decay became slower. Control runs with no poling identified a background of 0.097 ± 0.005 V. A single-layer prototype with a capacitance of 0.15 nF could not resolve the return voltage because of drift, implying that a specimen capacitance of 14.75 nF is sufficient to resolve return voltage with a cheap buffer. Using a polypropylene reference capacitor and following the same protocol, the instrumental contribution was 4.5 ± 0.1 mV (less than 1% of the smallest $V_{\max}$ measured).**

***Index Terms*—Dielectric absorption, electrometer, poly(vinyl chloride), return-voltage measurement.**

I. Introduction

If a charged capacitor is shorted and then reopened, the voltage will not stay at zero but will reappear as the dielectric relaxes its polarization. The dielectric becomes polarized when the capacitor is first charged, and its relaxation reintroduces charge onto the capacitor plates. This effect, dielectric absorption, was first quantitatively described for the case of the Leyden jar by Kohlrausch [1], and its time dependence reveals broad, non-Debye relaxation, similar to that found in disordered solids [2].

Furthermore, dielectric absorption plays an important role in high-voltage engineering through return-voltage measurement (RVM). The shape of the dielectric polarization spectrum can be deduced from the return-voltage peak and the occurrence time of the peak, measured as a function of charging time [3]–[5]. The measuring instrument must have an electrometer-grade input, otherwise the open-circuit recovery process will be disturbed by any measuring current.

The present work indicates that a standard CMOS buffer with a handheld multimeter is suitable for resolving RVM transients in common plastics if the sample has a sufficiently large capacitance. The peak voltage, the time to peak, and the decay of RVM transients in multilayer plasticized-PVC capacitors all depend on the time for which the capacitor is poled. Reproducibility and unpoled background data are presented.

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II. Principle

For a constant charge Q on the electrodes, the voltage can be expressed as $V = Q/C$, where C is the capacitance of the specimen. Poling at a voltage V_p over a time period t_p creates a relatively quick geometric polarization component and a slower one that will relax with time. The quick component can be nullified by shorting the electrodes, which removes the free charge and the quick component, but not the slow component. When the short is removed, this component will relax [6], recharging the electrodes and causing the voltage to rise to a maximum $V_{\max}$ at a time $t_{\max}$, after which bulk and surface conduction cause it to decrease again. Longer poling times are expected to charge more of this slow component, leading to a later and slower release of more charge.

Also, any current I drawn by the measuring circuit produces a drift $dV/dt = I/C$. The response of the sample does not depend on the area of the sample, because both the returned charge and C are proportional to the plate area. Increasing C therefore reduces the drift without changing the signal, which is the design principle of this work.

III. Apparatus and Method

A. Specimen

Commercial plasticized polyvinyl chloride (PVC) sheets (30 sheets, nominal thickness 200 µm) were systematically interleaved with aluminum-foil electrodes of 9×9 cm. Centralized on the PVC sheets, each electrode was surrounded by a PVC margin of 1.3–1.7 cm. One copper-tape tab was attached to each foil electrode, with tabs from alternating electrodes extending from opposite sides of the stack; the tabs on each side formed a bundle, and each bundle was held in place with staples to make metal contact through the native

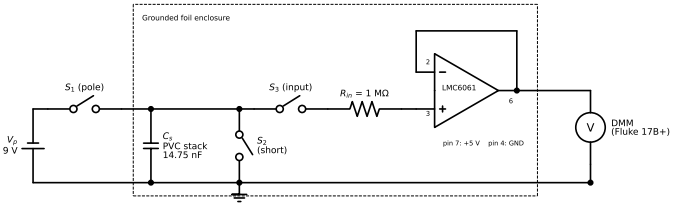


Fig. 1. Measurement circuit. The specimen C_s is poled through S_1 with S_3 open, shorted through S_2 for 10 s with S_3 closed, and released by opening S_2 at $t = 0$. An LMC6061 unity-gain follower with a 1 MΩ input resistor buffers the specimen voltage to a handheld multimeter. The specimen and buffer are inside a grounded foil enclosure.

oxide layer. The entire stack of 31 electrodes and 30 sheets of plastic (total thickness 6 mm) was held between insulating card boards by four binder clips. Based on electrical measurements, we determined a capacitance of 0.5 nF per layer and a total capacitance of 14.75 nF for 30 layers, indicating an effective permittivity of ≈1.4, likely due to micro air gaps between the foil and the sheets of plastic. All measurements were made with this specific structure, which was preconditioned by 24 hours of short circuit to clear charge accumulated during handling.

B. Front End

The buffer front end was composed of a standard CMOS operational amplifier, the LMC6061, with a typical input bias current of 10 fA [7]. The non-inverting buffer was implemented with unity gain and powered from a 5 V USB line, as shown in Fig. 1. To protect the buffer input, a 1 MΩ resistor was placed between the specimen and the buffer input, mounted on a flying lead insulated with electrical tape; the reference-capacitor test (Section V) shows that its leakage is negligible. At 5 V, the input common-mode range is guaranteed to extend to $V^+ - 2.3$ V (2.7 V) at 25 °C [7], well above the recorded return voltages. The buffer was tested with a 1.618 V cell, which produced an output of 1.618 V as expected, and with its input grounded, which gave an output of 0 V. The output meter (a Fluke 17B+) was used on its 4 V range (resolution 1 mV, accuracy ±(0.5% + 3 counts)) for the PVC trials and its 400 mV range (resolution 0.1 mV, accuracy ±(1.0% + 10 counts)) for the reference-capacitor runs, with an input impedance of >10 MΩ [8]. Video recordings of the meter display (at 30 fps) were taken. The specimen and buffer were both held in a grounded, foil-lined box, with the poling battery and meter outside.

C. Protocol

All experimental trials were carried out after the specimen had been shorted for a minimum of 90 minutes, and for a minimum of 8 hours after each 1800 s trial. In each poling cycle, the specimen was poled at $V_p = 9.56$ V (measured at the start of the campaign; nominal 9 V battery) for $t_p = 60$, 120, 600 or 1800 s, with the buffer disconnected. The short was then applied to the specimen for 10 s with the buffer connected, and trials proceeded only if the meter showed 0 V during the short. The end of the short defined $t = 0$. $V_{\max}$, $t_{\max}$, $V(300\ \text{s})$ and $V(600\ \text{s})$ were recorded. Each day the conditions were interleaved between trials, with the 1800 s cycle always performed last so that the specimen recovered overnight. Temperature within the enclosure was observed to be within 26.9 to 27.8 °C. Control experiments were also performed without the poling step, but following the same procedure as above. For the instrument check, a polypropylene film capacitor (measured capacitance 10.0 nF, rated 400 V) was used as a replacement for the specimen and was subjected to the same conditions ($t_p = 600$ s, $n = 2$), plus one run without voltage.

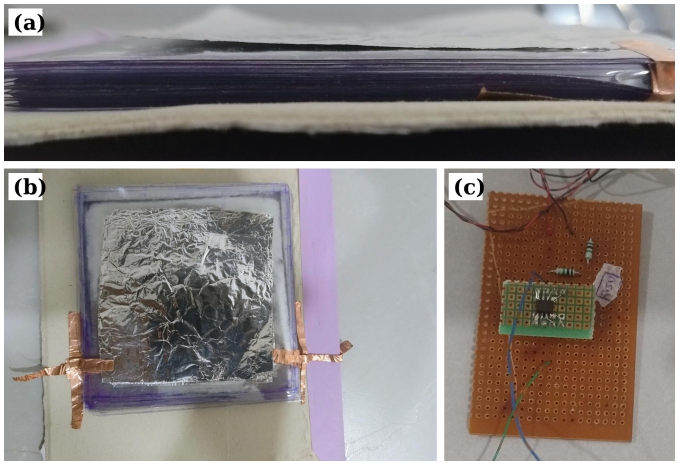


Fig. 2. (a) Side view of the 30-layer PVC/aluminum-foil stack with a copper-tape tab bundle. (b) Top view showing a 9×9 cm electrode, the PVC margin, and tabs exiting opposite edges. (c) Buffer board with the LMC6061 on an SOIC adapter; the two resistors visible on the board are left from an earlier test and are not connected.

Fourteen trials are reported ($n = 3$ or 4 for each condition). Two further trials were removed because of instrument faults: a 60 s trial with a reading stuck at 1.300 V ($V(300\ \text{s}) = V_{\max}$), and a 120 s trial affected by a supply transient when the enclosure was accidentally left ungrounded. Data are reported as mean ± one standard deviation. $t_{\max}$ values are quoted with an uncertainty of ±5 s in all cases, set by the flatness of the peak and the human response time in starting the timer. Only one run was read from video at 1 s intervals; for the others, $t_{\max}$ was timed by hand.

IV. Results

Fig. 3(a) shows a representative transient, with the voltage rising to a broad maximum within 1 min, then the rate of decay is so slow that approximately 50% of $V_{\max}$ remains even after 600 s. The blank runs are relatively flat with a plateau of 0.097 ± 0.005 V ($n = 3$); they are plotted on the figure and are subtracted where shown. Fig. 3(b) shows all 14 runs.

Table 1 and Fig. 4 summarize all conditions. $V_{\max}$ monotonically increases from 0.584 V (6.1% of V_p) to 1.295 V (13.5% of V_p) with t_p, the rate falling from about 0.9 V per decade for a t_p of 60–120 s to 0.3 V per decade for a t_p of 600–1800 s. $V_{\max}$ varies by at most 1.5% from run to run (which is 80 times smaller than the $V_{\max}$ increase over the entire t_p range). $t_{\max}$ monotonically increases from 48 ± 5 s to 66 ± 5 s,

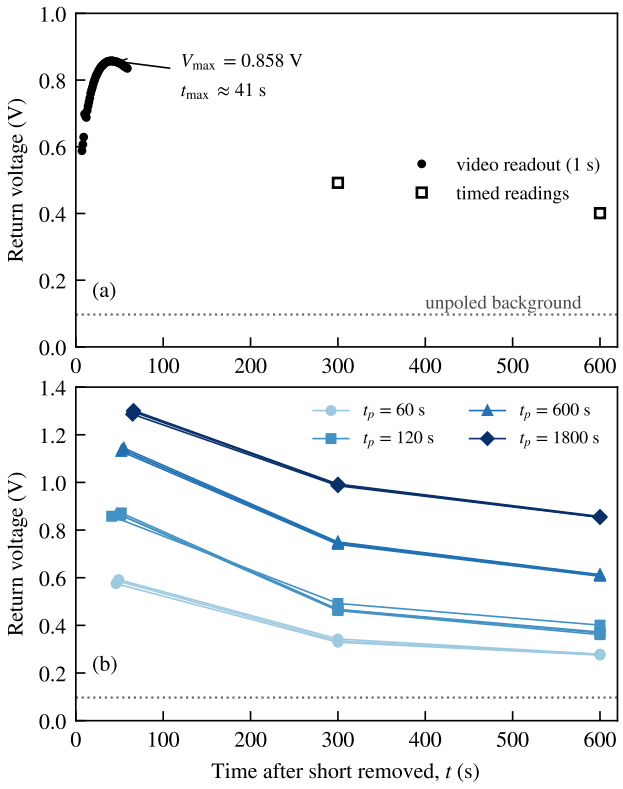


Fig. 3. Return-voltage transients. (a) Run after 120 s poling: dots, 1 s readout from video; squares, timed readings at 300 and 600 s. (b) All 14 runs: $V_{\max}$ at $t_{\max}$, $V(300\ \text{s})$ and $V(600\ \text{s})$, joined by straight lines. Dotted line: unpoled background.

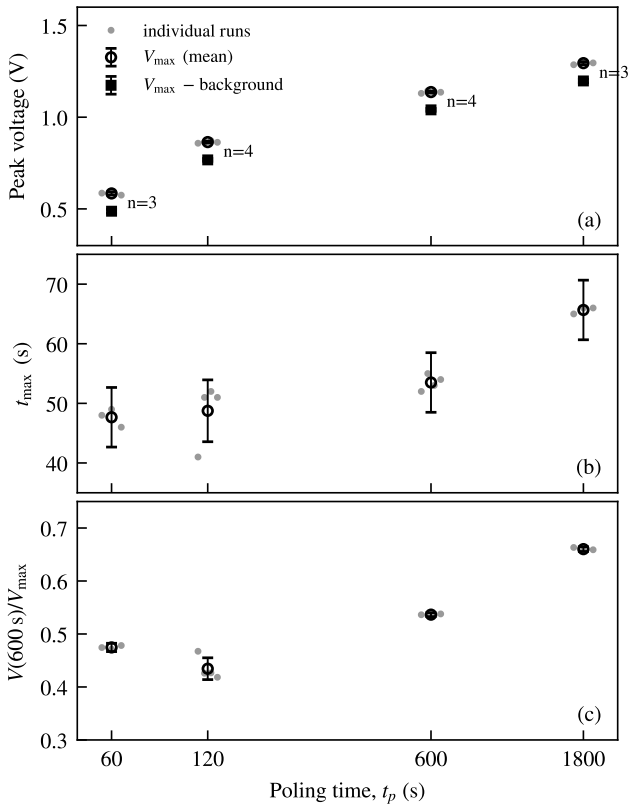


Fig. 4. Dependence on poling time t_p. Grey dots: individual runs; open circles: means. (a) Peak return voltage, raw and background-subtracted; error bars (±1 SD) are smaller than the markers. (b) Time to peak (±5 s). (c) Fraction of $V_{\max}$ remaining at 600 s.

TABLE 1
RETURN-VOLTAGE PARAMETERS VERSUS POLING TIME (MEAN ± SD)

t_p (s)	n	$V_{\max}$ (V)	$V_{\max} - V_b$ (V)	$t_{\max}$ (s)	V_{600} (V)	$V_{600}/V_{\max}$
60	3	0.584 ± 0.009	0.487	48 ± 5	0.277 ± 0.002	0.47
120	4	0.864 ± 0.006	0.767	49 ± 5	0.376 ± 0.018	0.43
600	4	1.137 ± 0.006	1.040	54 ± 5	0.610 ± 0.003	0.54
1800	3	1.295 ± 0.008	1.198	66 ± 5	0.855 ± 0.002	0.66

$V_b = 0.097 \pm 0.005$ V (unpoled background, $n = 3$); $V_p = 9.56$ V.

an 18 s increase, about 2.5 times the combined uncertainty of ±7 s; the 60–600 s values overlap within uncertainty. The ratio of $V(600\ \text{s})$ to $V_{\max}$ varies between 0.43 and 0.47 for $t_p \leq 120$ s and reaches 0.66 for $t_p = 1800$ s.

V. DISCUSSION

A distribution of time constants explains these behaviors. With longer poling, charging the slowest modes increases the accumulated charge and adds to the returned charge, though each further mode contributes less to increasing $V_{\max}$, and moves $V_{\max}$ to a later $t_{\max}$. The extra charge returns more slowly, so the decay is also slower. This shift of $t_{\max}$ parallels the use of $t_{\max}$ as a diagnostic in RVM of power-system insulation [4], [5], although standard RVM scales the discharge time with the charging time, whereas a fixed 10 s short was used here.

The critical variable was specimen capacitance. The first single-layer specimen prototype (two outer electrodes, 0.15 nF), which drifted hundreds of mV/min in open circuit even when not poled, was not usable for measuring return voltages. The multilayer specimen (≈100× the capacitance) exhibited reproducible transients with that front end, and a stable unpoled background, as one might expect from the I/C argument of Section II. The prototype drift implies an input current of roughly 0.5–1 pA, well above the buffer's typical 10 fA bias, pointing to leakage or charge pickup at the input, which a larger C suppresses equally. The polypropylene reference capacitor, whose own dielectric absorption is small, gave $V_{\max} = 4.5 \pm 0.1$ mV ($n = 2$; 4.4 and 4.6 mV; meter accuracy ±1.0 mV) after 600 s of poling, fell to 0.6 mV at 600 s, and gave no measurable voltage unpoled (0.0 mV). Because part of this may be the reference capacitor's own absorption, this is an upper bound: the instrument contributed less than 1% of the minimum PVC return voltage and 0.35% of the maximum, so these measured transients are specimen, and not instrument, dominated. The zero unpoled reference output indicates that the 0.097 V unpoled PVC blanks originate in the specimen, not the instrument.

Limitations: The quantity of plasticizer in the commodity-grade PVC was not specified, and the humidity was uncontrolled. The 0.1 V background is due to the sample, though it is not yet known whether it comes from residual polarization or an electrochemical process. Only one voltage of poling was

attempted; only one temperature window (1 °C) was used, and so no attempt was made to determine field dependence or activation energy. The low effective permittivity suggests air gaps, and interfacial (Maxwell–Wagner) polarization at the foil–PVC interfaces seems likely, so the response is that of the stack assembly rather than of bulk PVC. The single video-timed run peaked about 10 s earlier than hand-timed runs at the same t_p, so hand timing may read late. A cross-check with a depolarization-current measurement was not made.

VI. Conclusion

A catalogue CMOS follower (typical input bias 10 fA) and a handheld multimeter, together with an intentionally large multilayer specimen, resolve return-voltage transients in a multilayer plasticized-PVC capacitor with a run-to-run reproducibility of 1.5% or better. During 60–1800 s of poling at 9.56 V, the maximum return voltage increased by a factor of approximately two, the time-to-maximum increased by around 40%, and the decay slowed. These are what would be expected from the sequential charging of the slower polarization modes. This inexpensive approach offers RVM-style characterization of polymer dielectrics.

Acknowledgment

Claude (Anthropic) was used to analyse video recordings of the multimeter display and transcribe the readings into tabular form, as well as to generate plotting code for Figs. 1, 3, and 4. The authors take full responsibility for the content of this paper.

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