Compensating for Time Dependent Charge Components in Hysteresis Loops

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Summary

- The authors have developed a mathematics-based procedure for deriving the ferroelectric hysteresis of a leaky capacitor.
- The algorithm requires as its inputs two hysteresis loops measured a different frequencies on the same sample.
- The procedure is an *exact* solution as long as the ferroelectric property of the sample does not change between the two test frequencies.
- The procedure will correct for non-linear leakage characteristics.
- Radiant is adding a new filter to Vision to perform this operation.

Simple Resistance Compensation

- Since the original RT66A Ferroelectric Test System in 1989, Radiant has used the triangle wave as the forcing function for hysteresis.

- The triangle wave has a constant ΔV/Δt ratio so calculating the contribution by linear resistance to a measured hysteresis becomes:

$$Q_{R(n)} = Q_{R(n-1)} + \frac{\left[n \times \Delta V \times \Delta t\right]}{R} \qquad \text{Eq (1)}$$

where n = execution point #.

- The RT66A offered a simple compensation algorithm using Eq (1) with the measured resistance of the sample to subtract the linear resistance charge from the hysteresis.

- The algorithm worked and the loops looked better, but they were not correct. Dynamic leakage during the loop *is not linear*.

- We dropped that function from the library for our testers.

Current Compensation

- Meyer, Waser, Prume, Schmitz, and Tiedke[1] in 2005 proposed a technique for correcting the dynamic leakage component in the hysteresis loop of a leaky capacitor.

- The technique assumes that
  - the current through the leakage source is frequency *independent*
  - and the current through the ferroelectric sources is frequency *dependent*.

Subtracting the measured hysteresis current from two tests at different frequencies will eliminate the leakage contribution.

$$I_{comp}(\omega) = \frac{\omega}{(\omega_2 - \omega_1)} \times [i(\omega_2) - i(\omega_1)] \qquad \text{Eq(2)}$$

- $I_{comp}(\omega)$ is then integrated to generate the polarization hysteresis curve.

- The technique will work with aixACCT testers which measure current but will not work with Radiant testers which directly measure charge.

[1] Meyer, et al. in APL 86, 142907 (2005)

Charge Compensation

- Compensating the charge measurement requires a different equation.
- The starting equation is:

$$Q_{total(n)} = Q_{total(n-1)} + \Delta Q_{F(n)} + \frac{[\Delta V_n \times \Delta t_n]}{R_n} \qquad \text{Eq (3)}$$

- The (n) subscripts in Eq(3) mean that any forcing waveform may be used and that the value of R may change from one measurement point to another.
- $\Delta Q_{F(n)}$ must be constant with frequency so that subtracting two hysteresis loops taken at different frequencies leaves only the leakage component.
- The compensation equation, derived from Eq (3), becomes:

$$Q_F(\omega_2)_{comp} = Q_{total}(\omega_2) - \frac{\omega_2}{(\omega_2 - \omega_1)} \times [Q_{total}(\omega_2) - Q_{total}(\omega_1)] \qquad \text{Eq (4)}$$

at each point (n) in the measurement.

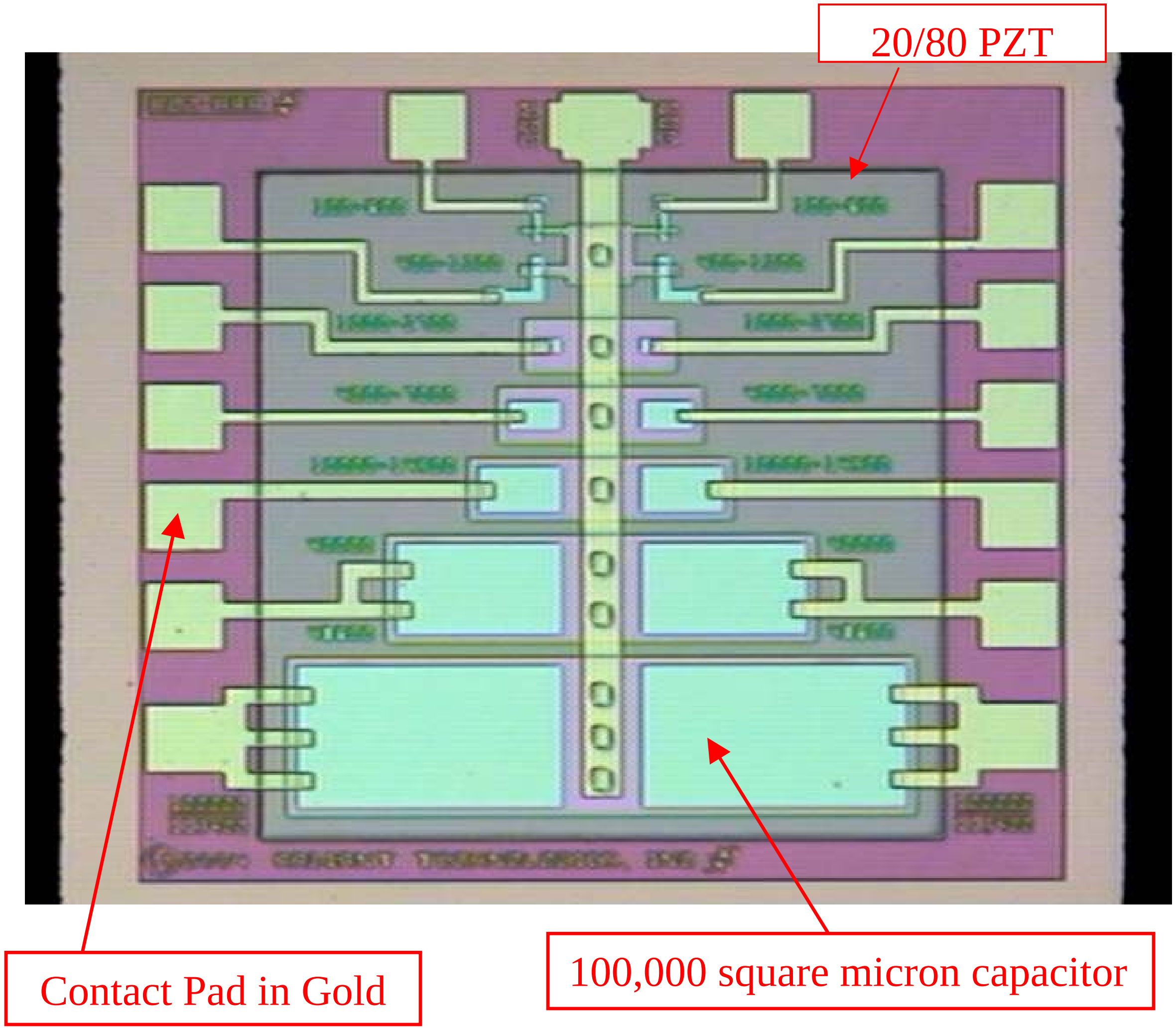
- Subtracting one measurement from another calculates corrections for all points in parallel.

Experiment

- Measure a single ferroelectric capacitor at two different frequencies.
- Check that the hysteresis loops at the two frequencies are essentially equivalent.
- Connect a resistor in parallel with the ferroelectric capacitor and measure again at the two frequencies.
- Apply the compensation algorithm to the hysteresis loops taken with the parallel resistor.
- Compare the compensated loops with the original ferroelectric capacitor loops taken in Step 1 above.

Capacitor to be Tested

- 0.26µ 20/80 PZT
- Platinum electrodes
- TiOx/SiOx ILD
- Chrome/Gold metallization
- 5V saturation
- Will withstand unlimited exposure to 9V.



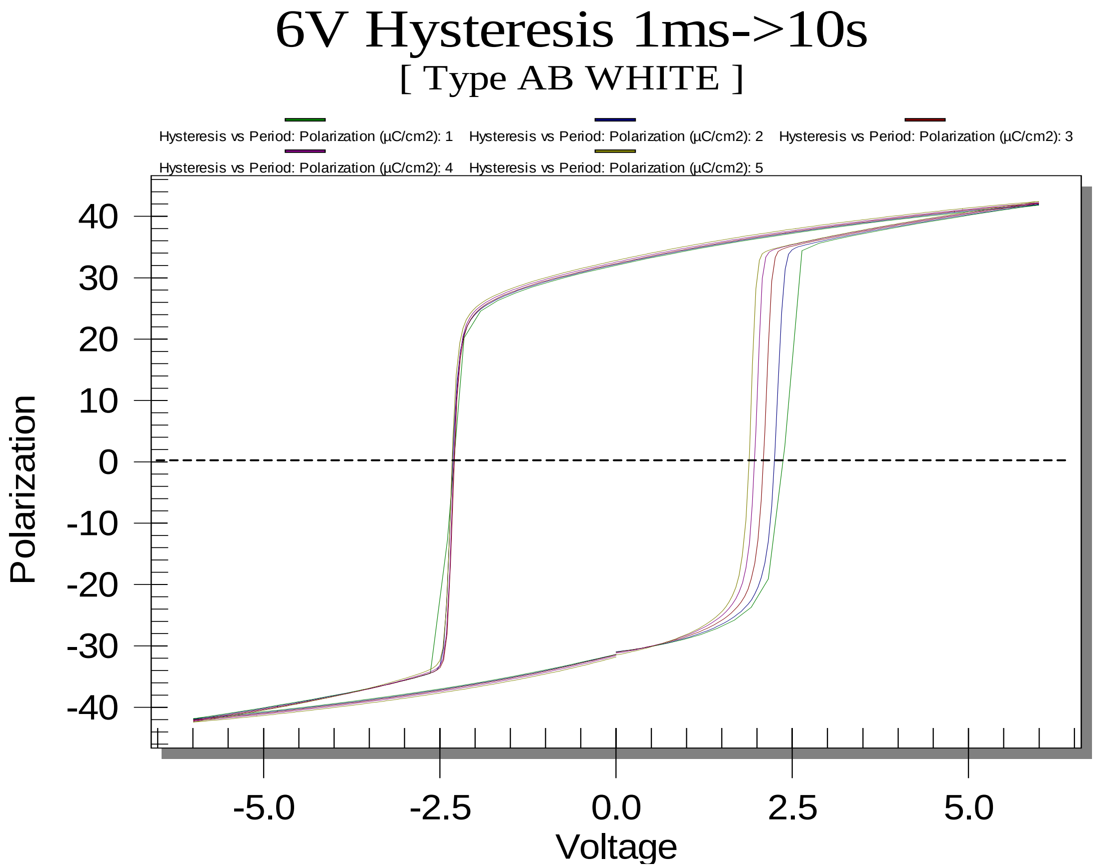
20/80 PZT

Contact Pad in Gold

100,000 square micron capacitor

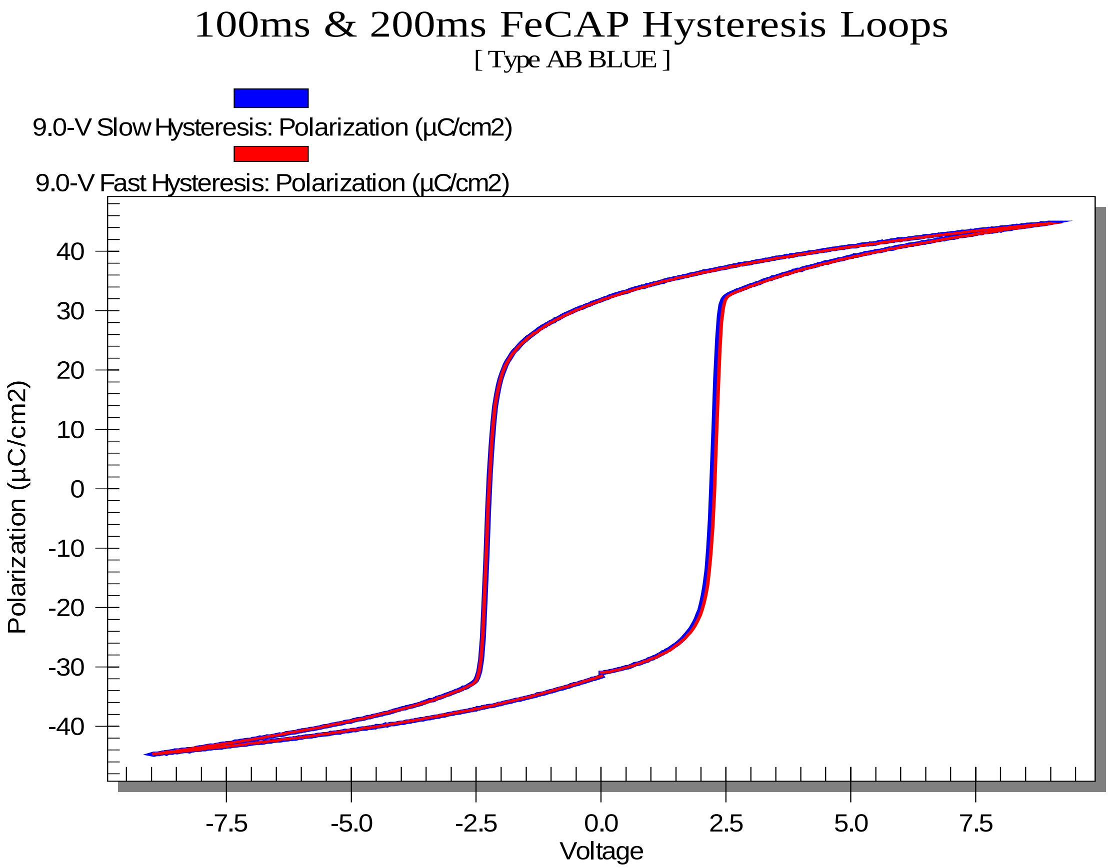
Capacitor Properties

Typical hysteresis vs period from 1millisecond to 10 seconds for the Type AB capacitor.



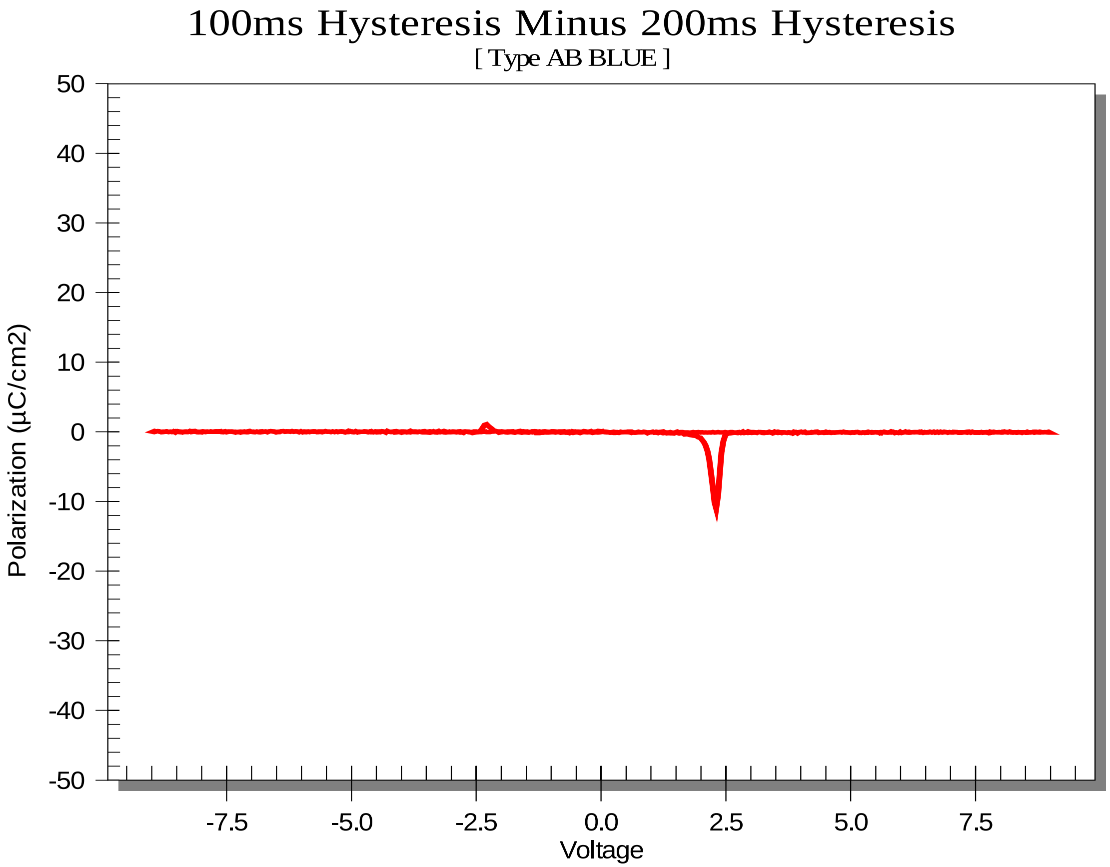
The coercive voltage changes significantly with frequency. A x10 change in frequency is too large for the algorithm. Use x3 or smaller.

Hysteresis at 100ms and 200ms



There are two loops in the plot with 100ms and 200ms periods. This capacitor meets the criteria for minimal change in frequency response in the test range.

Hysteresis at 100ms and 200ms



The plot above is the difference between the 100ms and 200ms loops. Of the previous slide. There is a slight shift in the coercive voltage for the two test periods.

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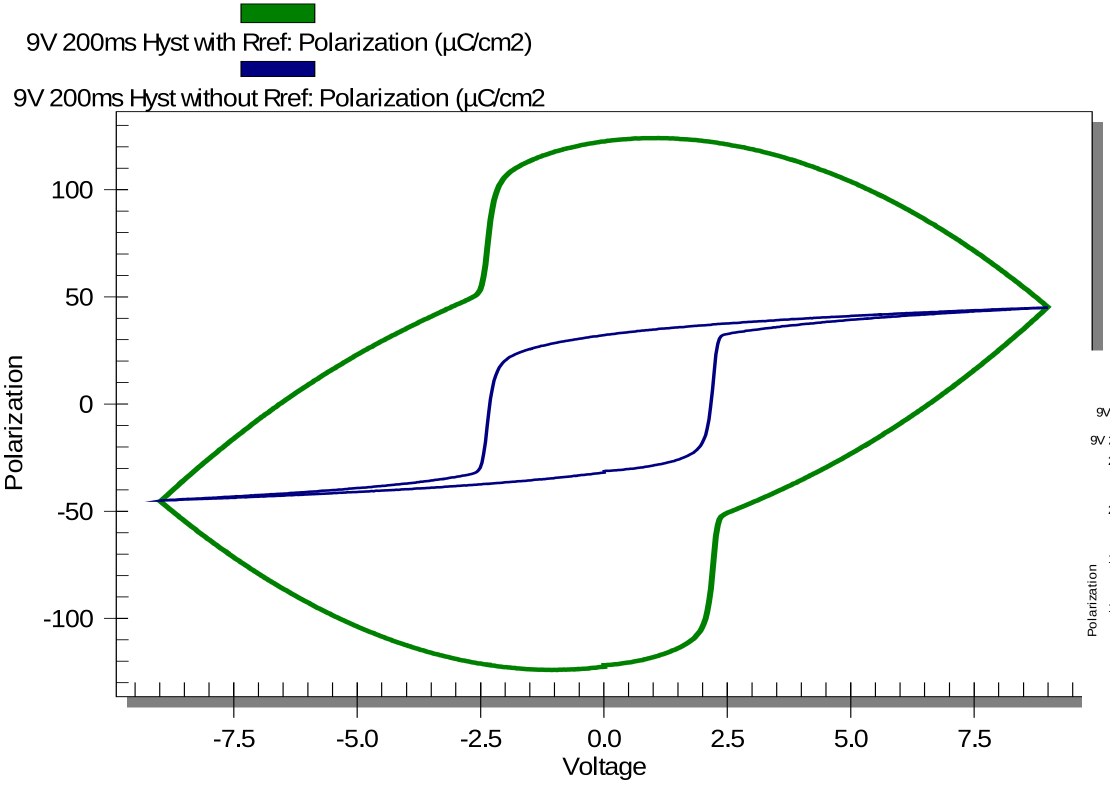
Hysteresis with Parallel Resistor

Below is a 200ms loop of the sample capacitor both with and without a 2.5MΩ precision resistor in parallel to the capacitor.

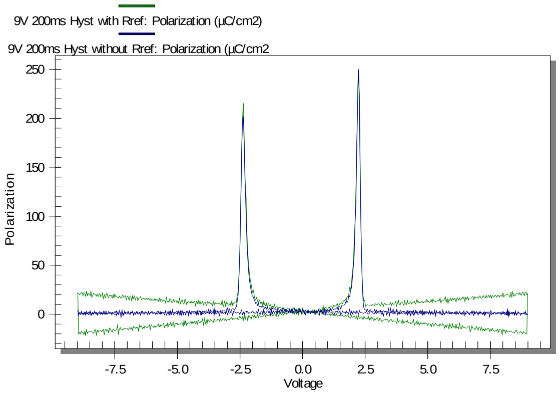
Hysteresis Loop with and without Parallel Resistor

[Type AB BLUE]

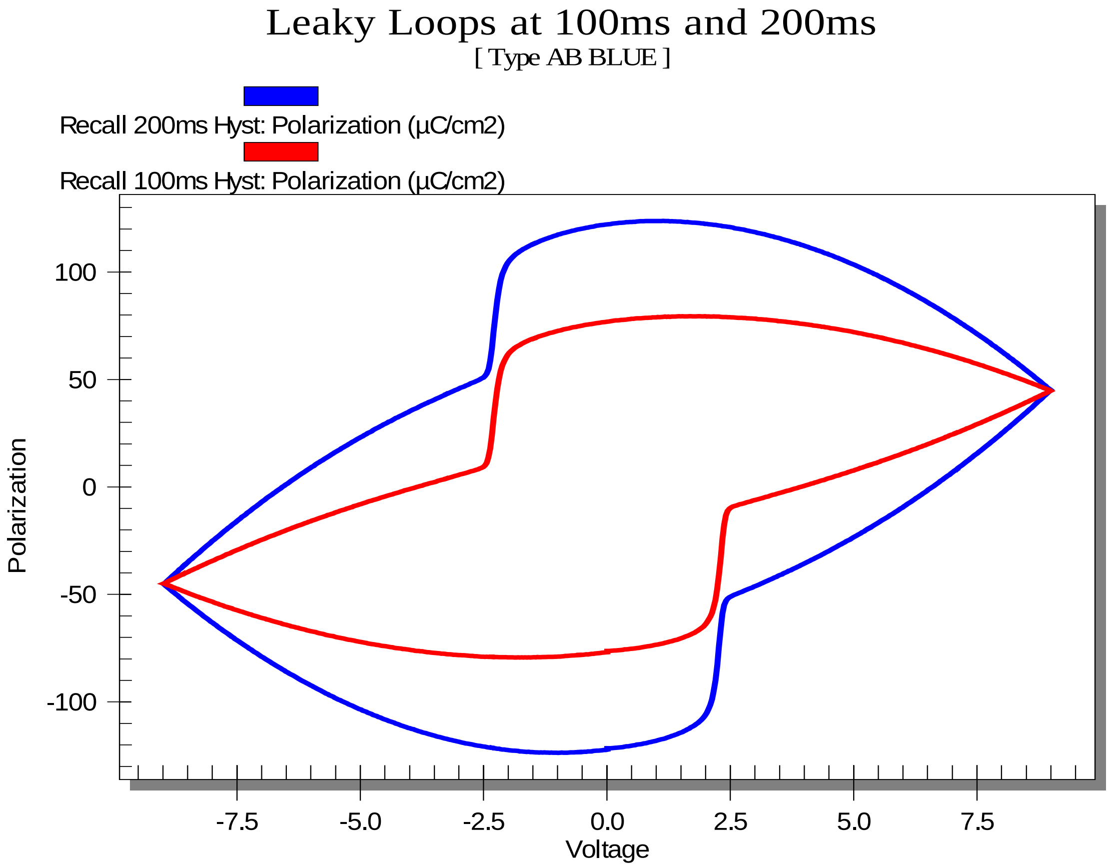


nCV with and without Parallel Resistor

[Type AB BLUE]

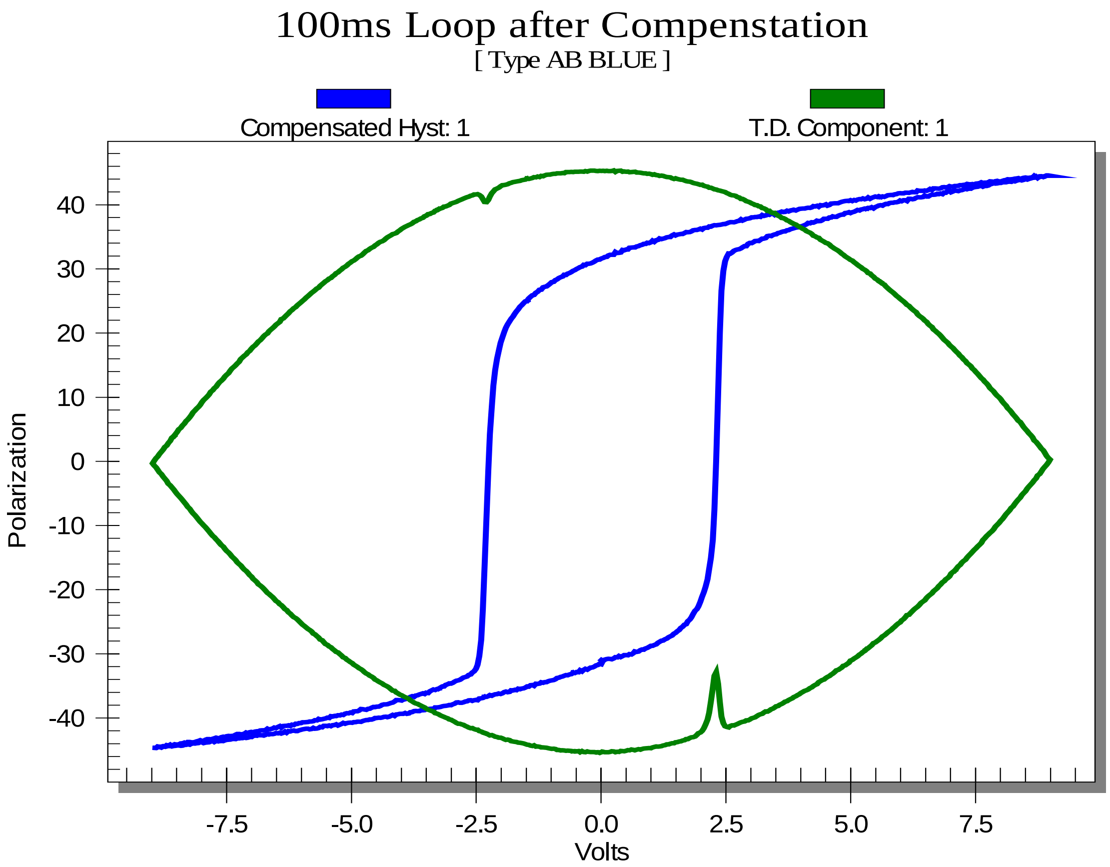


The Leaky Loops



Above are the 100ms and 200ms loops of the sample capacitor with the 2.5MΩ precision resistor in parallel to simulate leakage.

The 100ms Compensated Loop



Above is the compensated 100ms ferroelectric hysteresis loop and its leakage component derived from the 100ms and 200ms loops using Eq(4).

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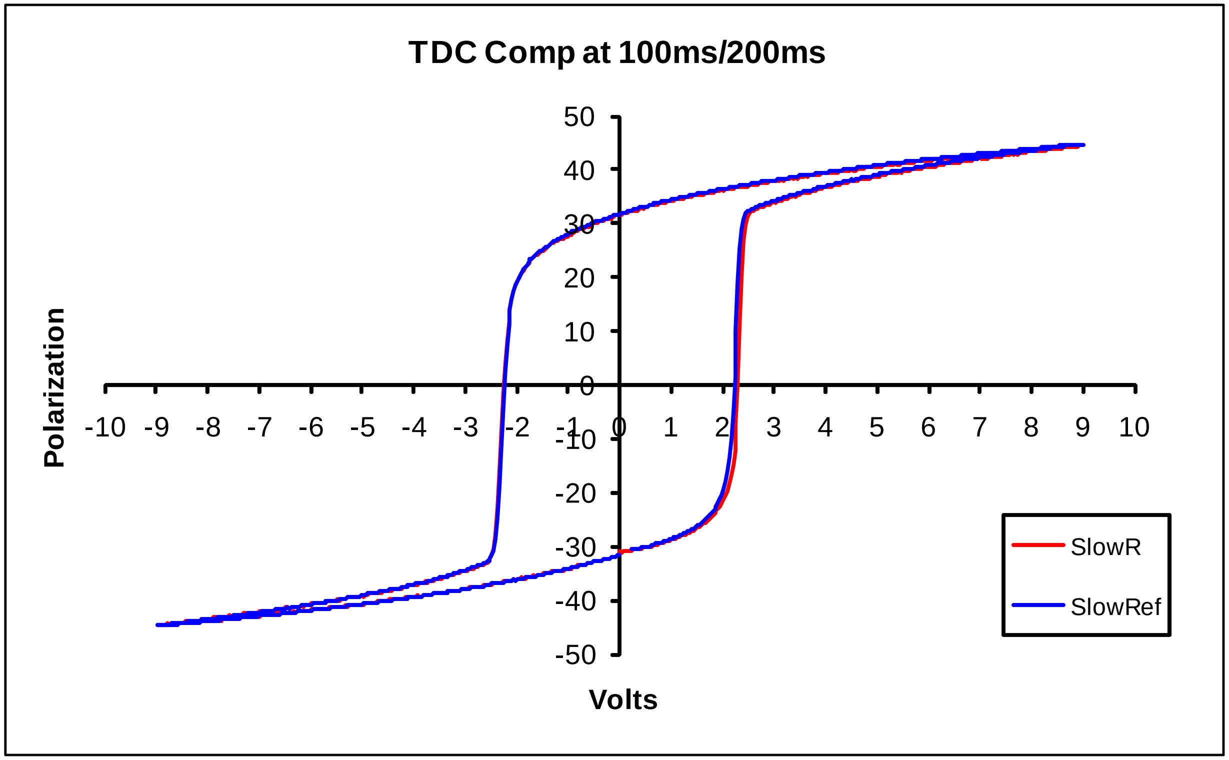
Compensated vs Original Loop

Below is a plot of the 100ms compensated loop plotted over the original 100ms loop of the ferroelectric capacitor without the parallel resistor.



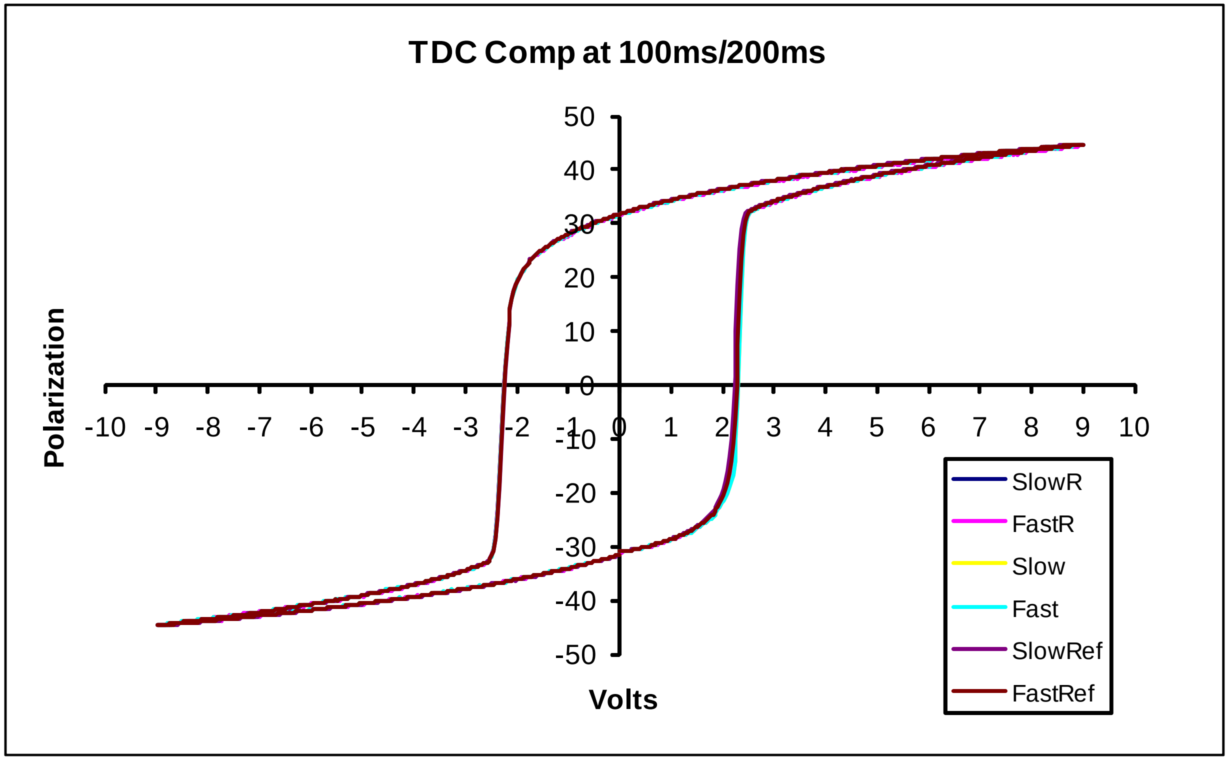
It is nearly an identical match!

All Six Loops

The algorithm was executed to find the compensated 200ms loop. As well, it was applied to the original hysteresis loops taken without the parallel resistor. All six loops for the 100ms/200ms combination are plotted atop each other below.

Original
- 100ms
- 200ms

Compensated
- 100ms
- 200ms
- 100ms with resistor
- 200ms with resistor



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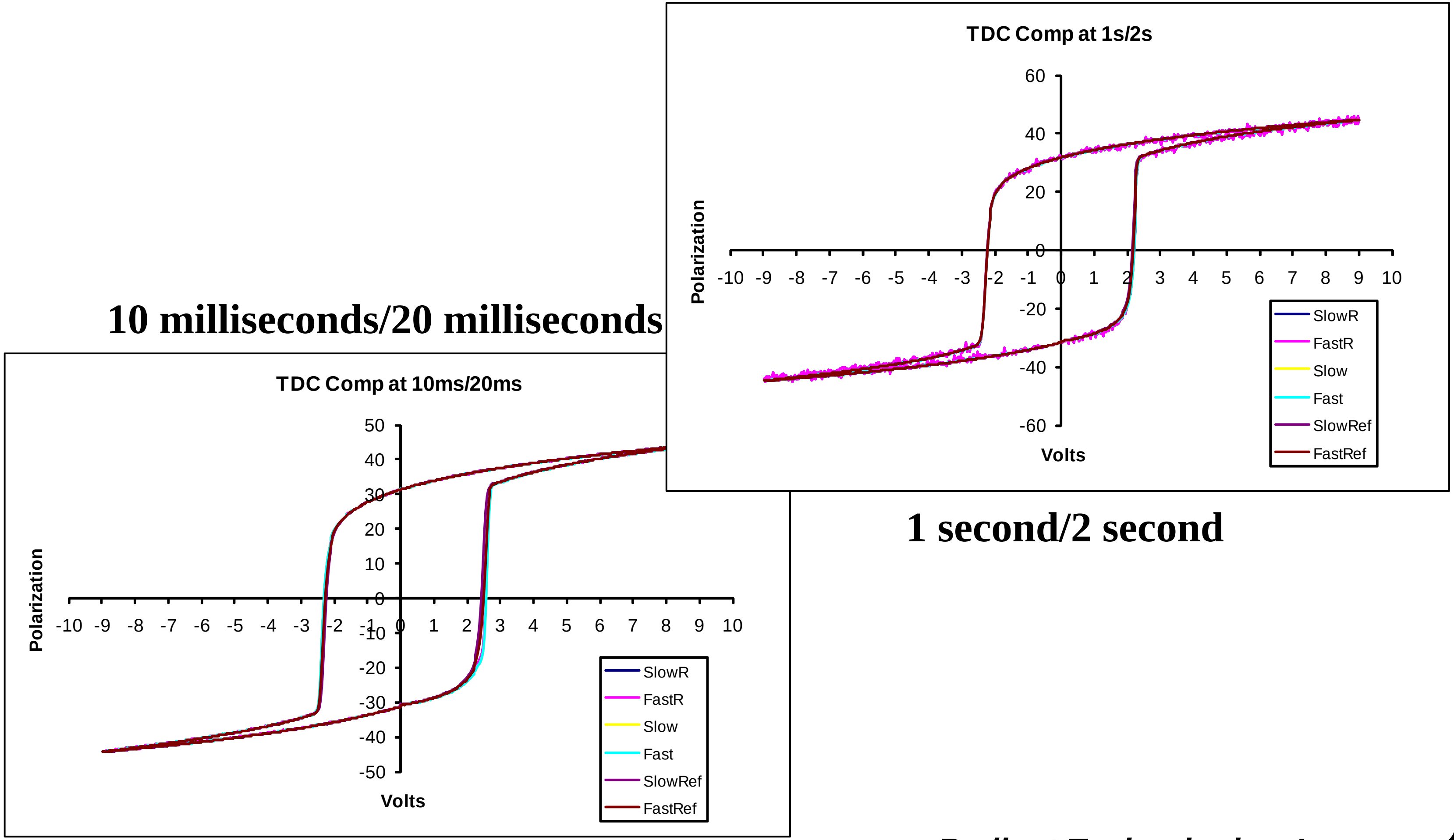
Other Frequencies

The “Six Loop Plot” for tests run at 10ms/20ms and 1s/2s for the sample are shown below.



10 milliseconds/20 milliseconds

1 second/2 second

Analysis

- Eq (4) appears to work extremely well for a linear leakage contribution.
- No coupling exists in the algorithm between the correction at point (n) and points (n-1) or (n+1) or any other measured points so the algorithm should properly correct for non-linear leakage components as well.
- The algorithm and the results indicate that this solution is an *exact* solution, not an approximation, as long as the limitations listed next are not exceeded.
- The algorithm may be used not only to correct the hysteresis loops of leaky samples. Its most important contribution may be as a tool to better understand the inner workings of ferroelectric capacitors.

Limitations

- Eq (4) *will only work* if ferroelectric component of the sample capacitor is *constant* at the two test frequencies.
- The calculation is a point-for-point parallel computation. Therefore, the number of test points in both measurements must be equal.
- The test voltage and test waveform for the two measurements must also be identical.
- Because ageing effects change the shape of the hysteresis loop, the two frequency tests should be executed within close temporal proximity.
- This algorithm assumes discrete sample points to establish $\Delta V/ \Delta t$. It cannot be applied to a continuous, analog comparison.

Conclusion

- The following equation will derive the ferroelectric polarization hysteresis for a capacitor that has other parasitic current sources.

$$Q_F(\omega_2)_{comp} = Q_{total}(\omega_2) - \frac{\omega_2}{(\omega_2 - \omega_1)} \times \left[Q_{total}(\omega_2) - Q_{total}(\omega_1) \right]$$

- The solution is an exact solution as long as the two test frequencies ferroelectric are close enough that the ferroelectric hysteresis loop does not change between the two frequencies.