DESIGN CONSIDERATIONS FOR CHARACTERIZATION OF CAPACITORS

by

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candidate for the Master of Science degree*.

*We also certify that written approval has been obtained for any proprietary material contained herein.

Dedication

Dedication text

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Preface

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List of Abbreviation

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Glossary

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Abstract

0.1 Previous Abstract

This paper presents an analysis of capacitor performance at up to 600VDC bias. The analysis is accomplished through small-signal impedance testing, charge and discharge time constant measurements, and leakage current measurements. All tests are recorded by means of multiple ADCs and computer analysis.

0.2 Current Abstract

This paper presents an analysis of capacitor performance degredation at up to a 600VDC bias. It proposes a testing method through small-signal impedance testing, charge and discharge time constant measurements, and leakage current measurements. Circuit analysis and itinial prototypes will be discussed.

1 Background

The following is a list of the questions that I will be answering in my background section.

1. Where are capacitors used with a high DC bias?
   (a) What characteristics are the most important there?
   (b) What are the main failure modes?
   (c) What are the current specifications of the parts in use now?
   (d) What research is being done to develope better capacitors for this use case?
   (e) How do they currently evaluate the capacitors?
   (f) How would they benefit from my research?
2. What is the state of the art in capacitance measurement?
   (a) Impedance analyzers
   (b) Capacitance bridges
   (c) Hi pot testers
   (d) What are the good and bad points of each of these technologies?
   (e) Why do they not solve the problem that I stated?
   (f) Why does this technology not currently exist?
3. What work has been done similar to this in the past?
4. What are the important characteristics of capacitors?
5. Is there any evidence that a capacitor's properties will change over DC bias?

2 History of Capacitors

This section will chronolog the history of capacitors. It will link various introductions in the technology to advances in industry, and it will map the driving forces behind capacitor development.

Types of capacitors:

1. Leyden jars
2. ceramic
3. aluminum electrolytic
4. tantalum
5. polymer
6. metalized film
7. foil film
8. titanium

Driving forces for development:

1. scientific study
2. military
3. radio industry
4. consumer electronics

Significant players:

1. ...

2.1 Comments

*You talk about the different types of MLCCs but are not very clear as to how the differences are achieved. *The only company you mention is Sprague but Cornell Dublier is also a big and I would need to think about others such as Aerovox. I am sure there are others. *You said very little about electrolytics in your discussion and the latest are low-voltage supercapacitors.

2.2 History

Capacitors have their origin in the invention of the Leyden jar by Peter van Musschenbroek of Leiden University in 1745. [12] It allowed for the storage of electrical energy for the first time in known history.

The Leyden jar was typically made from a glass jar with metal sheets spread on the inside and outside. Electricity could be stored by charging the jar with an electrostatic device and the removing the jar. This breakthrough in the study of electricity was exremely important to scientists, as it allowed electricity to be stored and then used later. [9]

The most common design for the Leyden jar was to use a glass jar with metal foil lining the inside and out. Then inner surface was typically charged via an electrostatic generator, while the outer surface was connected to ground. The charge would stay on the metal foil until a short or small resistance was connected between them. Charge could be stored this way, allowing scientists and showmen, to use greater amounts of charge than they could generate at any one moment.

Since the Leyden jar, many different types of capacitors have risen and fallen in prominence in the market. This section will cover the historical introduction of some of the major types.

Paper capacitors use waxed paper as a dielectric. They are primarily used in high voltage applications. But they are not preferred for much due to their high leakage and tolerances.[14] In 1876 Fitzgerald introduced wax impregnated paper dielectric capacitors with foil electrodes.[3, ch. 11] [14] They were typically used for power supply filtering in radios. In the early 1920s, they existed as tubes encapsulated in plain, bakalized cardboard, with bitman sealing the ends.[3, ch 3]

Impregnated paper capacitors used paper that was soaked in mineral oil. It was interleaved with metal foil and then rolled to make the capacitor.[20, ch. 8.2.1.1] During WW2, paper capacitors were upgraded with metal-cased tubes with a rubber end.[20, ch. 8.1] Metalized paper capacitors were created as a replacement for impregnated paper capacitors. They were constructed similarly with the improvement that one side of the paper dielectric was sprayed with metal.[5]

Karol Pollak discovered the principle of the electrolytic capacitor in 1886 while he was researching the anodization of metals. In 1897, he received a patent for the borax-solution aluminum electrolytic capacitor. In 1926, Julius Lilienfeld patented an electrolytic capacitor containing electrolyte soaked paper. Ralph D. Mershon developed the first practical, commercially available radio electrolytic capacitor. After the start of WW2, increased funding and effort was applied to the cause of electrolytic capacitors and technics such as "etching and pre-anodizing" greatly increased their reliability. [27]

In 1897, Charles Pollak received a patent for the borax electrolyte aluminum electrolytic capacitor. In 1936 Cornell-Dubilier opened a factory to produce aluminum electrolytic capacitors. These capacitors became more reliable after WW2, when the industry applied additional resources to develope the technology.[7]

M. Bauer of Germany invented the mica capacitor in 1874. The original mica capacitor was a "clamped" style capacitor, which was used through the 1920s.[28] Clamped style mica capacitors were eventually replaced by silver mica capacitors, which greatly increased mica capacitors' characteristics.[14].

Mica's inherent inertness and reliability allowed for extreme reliability and efficiency in a packaged capacitor.[25] The mica capacitor was heavily used in the radio industry due to its superb stability at RF frequencies and physical robustness.[19]

During WWI, mica capacitors began to be produced in large quantities. This was mainly due to it being able to survive shock from weapons better than its glass counterpart. Also, it allowed the capacitors to be shrunk to achieve the same purpose. [3, f. 37-41]

In light of mica supply chain problems and the emergence of ceramic capacitors during WW2, mica capacitors fell from prominence to a niche market.[1, Ch 3, Sec II]

The first glass dielectric capacitor was, in fact, the Leyden jar. While this early capacitor was used mainly for scientific experiments, commercial glass capacitors came later.

Glass tubular capacitors appeared in 1904 and were used in Marconi's experiments in wireless transmission. They were know as Moscicki tubes. They continued to be used in wireless communication until about WWI. [3, p. 102]

Scientists in Germany created the first steatite ceramic capacitor in 1920. [1, Ch 3 Sec II] [11] Also known as talc, this ceramic capacitor variant was able to closely match the temperature coefficient of mica.[6]

Rutile ceramic capacitors were introduced with a dielectric constant of 10 times that of steatite. It was typically blended with steatite to get a better temperature coefficient.

A ceramic composition wth barium titanate (BaTiO3) was first discovered in 1941. Barium titanate was quickly found to be able to exhibit a dielectric constant over 1000; an order of magnitude greater the best at this time (rutile - $Ti0_2$). It was not until 1947, that barium titanate appeared in its first commercial device, phonograph pickups.[10][5][1, Ch 3 Sec III] Today barium titanate is still seen in multi layer ceramic capacitors.

Multi-layer ceramic capacitors are the current leading technology in commercially produced units. They are divided up into three classes. Class 1 type MLCCs are known for their extremely good temperature characteristics. COG/NPO types can have 0-30ppm/^{o}C. These capacitors are typically made by combining TiO_2 with additives in order to adjust its temperature characteristics[16]. Additinally, class 1 ceramics have comparitively poor volumetric efficiency, and will tend to come in larger packages than class 2 ceramics of the same capacitance value. Class 2 types typically have worse temperature coefficients than type 1 types, but they have a much higher volumetric efficiency.They are constructed with a ferroelectric base material, typically Barium Titanate.[16]. Class 2 ceramic capacitors are the most common type of ceramics used. Class 3 types have very high capacitance, but a working voltage of several volts.[5][1, Ch 3 Sec VI][4]. They were originally developed as a potential replacement for liquid electrolytics, but have fallen out of favor due to the advances in Class 2 ceramics to the point where the gap between these two in terms of maximum capacitance is no longer viable[26].

Bell labs invented the first solid tantalum capacitor in 1956. They created it in conjuncture, and for, transistors.[3, f. 56-64] Tantalum capacitors typically have better characteristics than aluminum electrolytics, but have a lower maximum capacitance and working voltage.[14]

Sprague patented the first commercially viable solid tantalum capacitor in 1960. It offered an increased capacitance per unit volume and greater reliability.[21] In the 1970s, Sprague released the first surface mount tantalum capacitor.[22]

One of the historical problems with tantalum capacitors has been a limited supply of tantalum in the world market. This has occasionally caused price spikes in the material, hurting the tantalum capacitor market. As a result of the price spike around 1980, manufacturers created finer grain tantalum powders. This allowed a unit to be made with less overall tantalum, reducing price and package size.[8, ch 3.1]

3 Capacitor Parameters

3.1 Comments

*In Section 3.1 you could mention what characteristics are important for that application. And capacitors for switching power supplies are conspicuously absent. *Do you want to get into capacitor parameters such as stability, temperature operating range, working voltage, peak or surge current, etc

3.2 Practical Capacitor Uses

Before getting into the individual capacitor parameters, I will explain some of the basic uses for capacitors. Each of the individual parameters will be important and have a direct effect on the uses described here. One should be careful to remember that any model consisting of the parameters listed in this section (and others) only describes an approximation of what is happening inside of a capacitor. Models and capacitor parameters will never be 100% correct, but can be made with fairly high accuracy. As long as the designer understands the circumstances in which the models are accurate, he can use them to make a better circuit.

The most basic reason for wanting to use a capacitor is that it has the ability to store charge, which is close to the same thing as saying that it has the ability to store energy. It can store and release energy quickly to be able to react to the needs of the circuit.

3.2.1 Power Supply Bypassing

One of the most common uses for capacitors is to bypass a DC power supply. In the case of an Linear or DC-DC power supply, they are expecting a generally constant power supply. A portion of the noise (none DC voltage) on the line will be transferred to the output. Putting a capacitor from a power supply to ground acts as a local

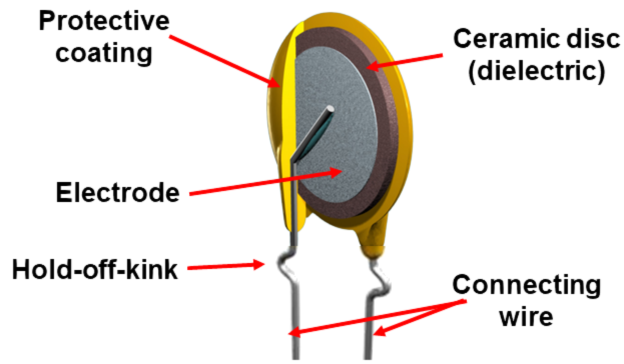

Figure 1: Bypassing Example

charge reservoir to smooth out noise on the line. See Figure 1.

Bypass capacitors are also put close to the power pins on IC chips. Especially with digital chips, high frequency switching causes surges of current to be drawn from the line. If not for having bypass capacitors, this would cause dips in the power line at the switching frequency. This effect can cause logical glitches that are very difficult to debug.

3.2.2 Analog Filtering

Another use for capacitors is in analog filtering. Take for instance the low pass figure in Figure: 2. The capacitor is used in this configuration to control which frequencies get passed to the rest of the circuitry. Low pass filters are needed in many application; a few of them being anti-aliasing, clock filtering, and integration.

3.2.3 DC Blocking

Designers often take advantage of capactors' characteristic of passing AC current while blocking DC current. As in Figure: 3, a capacitor can be used to block a DC offset before an amplifier.

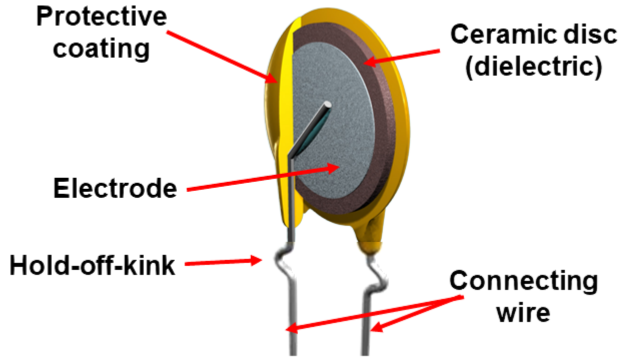

Figure 2: Low Pass Filter

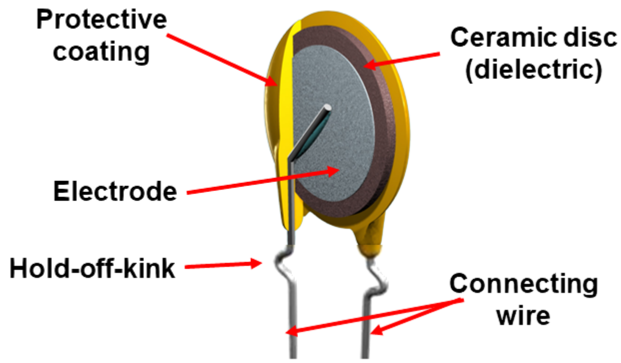

Figure 3: Using a capacitor in a DC blocking application

3.2.4 Power Factor Correction

The inductors in modern DC-DC switching supplies have required increased attention to the engineering phenomenon know as power factor. Any electrical load with an inductive component causes the supplied current phase to lag the voltage phase. This effect decreases the efficiency of the power distribution and also has the ability to cause stability issues. A capacacitor can be used as a simple, passive way to move the power factor back towards the ideal state (See Figure: 4). [18]

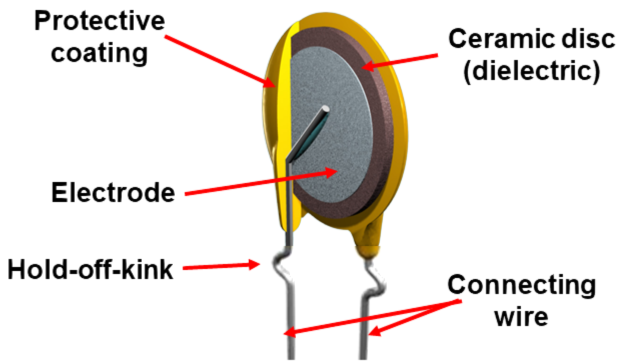

Figure 4: Power factor correction circuit

3.2.5 Oscillators

Capacitors are also used in oscillator circuits. – Add resonator from HnH.

3.3 Capacitance

There is a distinct difference between a capacitor and capacitance. While a capacitor's main characteristic is capacitance, it cannot be modeled entirely as such in most practical applications. There are various inductive and resistive components to a capacitor that are important in various circumstances.

$$C = \frac{Q}{V} \tag{1}$$

Capacitance is the ability to store electrical charge. Equation: (1) says that capacitance is stored charge that is spread throughout a volume. A device that can store a lot of charge in a small area has a large capacitance.The basic equation for a commercial capacitor is seen in Equation: (2).

$$C = \frac{\epsilon_0 A}{d} \tag{2}$$

When using a capacitor in a single-pole low-pass filter, the cutoff frequency can

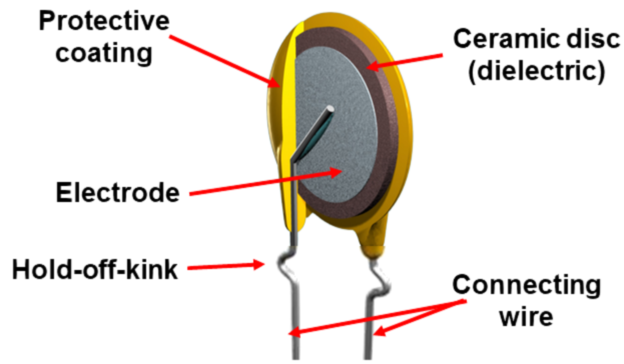

Figure 5: Changing Capacitance in a Low Pass Filter

be determined by Equation: (3). The circuit designer will choose a value for C and R in order to meet the cutoff frequency restraint.

$$f = \frac{1}{2\pi RC} \tag{3}$$

Varying the capacitance used in the filter will move the cutoff frequency and consequently get a different response in the filter. The effect of this can be seen in Figure: 5.

3.4 Impedance

The impedance of a capacitor is the "AC resistance" of the device. It determines the AC current that will flow when an ac voltage is applied to the capacitor via Ohm's law (Equation: (4)). An ideal capacitor has no resistive elements and is purely capacitive. Therefore, its impedance can be described via Equation: (5). The two main things to notice are that the impedance is frequency dependent and it is purely imaginary (reactive).

$$\vec{V} = \vec{I}\vec{Z} \tag{4}$$

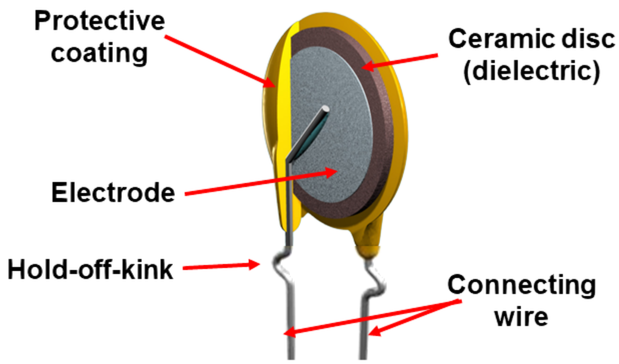

Figure 6: Ideal Capacitor Magnitude versus frequency

$$\vec{Z} = \frac{1}{2\pi j f C} \tag{5}$$

$$Z = |\vec{Z}| = \frac{1}{2\pi f C} \tag{6}$$

In most AC applications we look at the magnitude of the impedance. Real capacitors have a more complicated impedance, but with an ideal capacitor we can simplify the magnitude equation down to Equation (6)

When capacitors are used in bypassing power supplies, the idea is to have a low impedance for common or expected noise frequencies. One may be tempted to choose a large valued capacitor to use for bypassing a wide range of frequencies. This turns out to backfire in practical situations, due to other parasitics in a real capacitor. For any capacitor, the impedance equation is more complicated, and the impedance value will begin to increase with frequency after some point. This will cause the designer to choose several different valued capacitors in parallel when bypassing a power supply or sensitive component. We will see later that the frequency plot of a capacitor will end up being more complicated than the simplified version seen in Figure: 6.

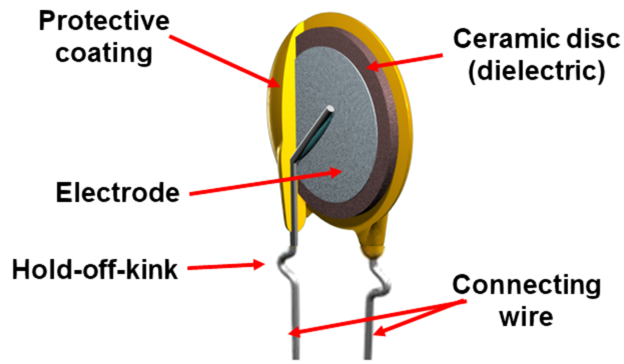

Figure 7: Low-Pass Filter Phase

3.5 Phase

The phase of a combination of resistive and reactive components can be written as in Equation: (7).

$$\phi = tan^{-1}[\frac{X_c}{R_c}] \tag{7}$$

For an ideal capacitor, having no resistance and only capacitance, the phase angle is only written as:

$$\phi = -i = -90^0 \tag{8}$$

The practical implication of this can be seen in the phase response of a low pass filter (Figure: 7). The capacitor introduces a phase lag relative to the input signal's frequency. If you would compare the input and output signals in time, the output's peak would lag behind the input's by the phase amount predicted in the phase response.

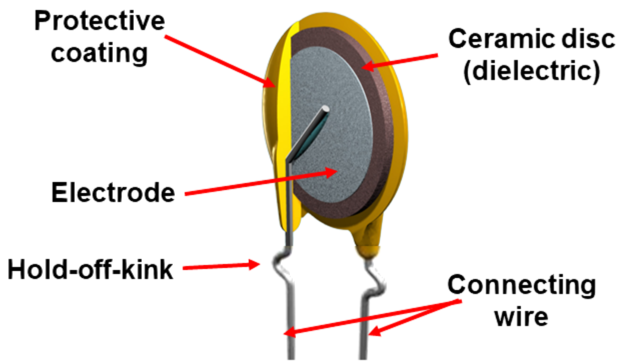

Figure 8: Capacitor ESL Model

3.6 ESL

The Equivalent Series Inductance (ESL) of a capacitor is a lumped estimate of all of the inductive components of a capacitor. It is typically modeled as an inductor in series with the bulk capacitance (See Figure 8).

Adding ESL to the capacitive model creates a new impedance equation (Equation: (9)). Note that for L<<C, this equation simplifies to Equation: (5) for low frequencies.

$$\vec{Z}_c = \frac{1 - \omega^2 CL}{j\omega C} \tag{9}$$

$$\phi = Phase \tag{10}$$

Similarly, Equation: (10) shows that the phase of the capacitor is also affected at higher frequencies

Figure: 9 shows a graphical representation of a capacitor's magnitude and phase once ESL is considered. This plot shows that at a certain frequency, a capacitor's impedance will begin to increase with frequency. This means that a bypass capacitor will only be effective up to a certain frequency. Typically, the this frequency point

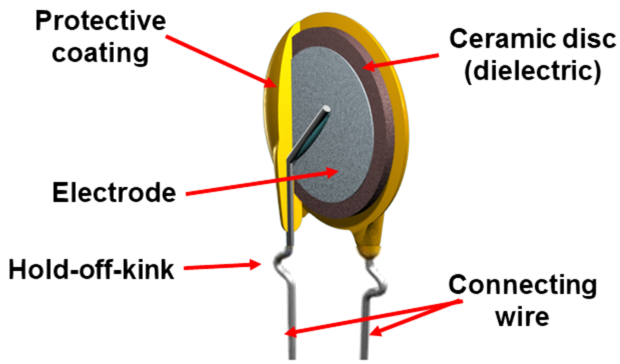

Figure 9: ESR+ESL Impedance-Phase Plot

and the capacitor's value have an inverse relationship. This is why you will see power supplies and sensitive chips being bypassed by a range of widely different valued capacitors.

3.7 ESR

A real capacitor is more complicated than the ideal single capacitor model. One of the most used parameters is the Equivalent Series Resistance (ESR). ESR is the practical result of the fact that the materials used to create the capacitor have resistance. In simple cases, this can be approximated by a resistance in series with a capacitor (See figure: 10).

ESR becomes is important when thinking about DCDC switch mode power supplies. The converter's output voltage will have some ripple voltage on top of the DC output. This produces a ripple current through the capacitor. The capacitance element experiences no losses, but the ESR dissipates power according to Equation: (11)

$$P_{ESR} = I_{C,RMS}^2 * ESR[15] \tag{11}$$

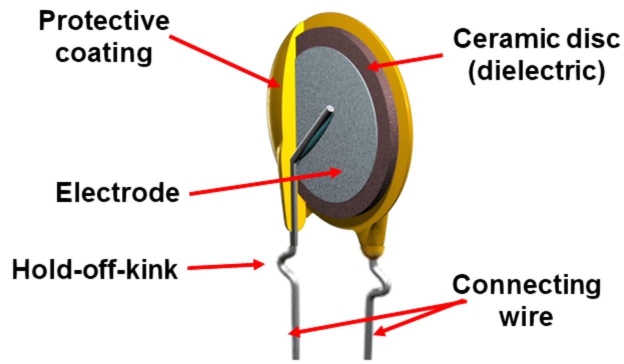

Figure 10: Capacitor ESR Model

$$\vec{Z}_c = ESR + j * (\omega L - \frac{1}{\omega C})[15] \tag{12}$$

Another important thing to note about ESR is that even though it is modeled as a resistance, it is not constant across all frequencies. It is a simplification of resistive and capacitive elements in a capacitor that are dominated by resistance.

3.8 Resonance Frequency

Once C, ESL, and ESR are included into the capacitor model, a parameter know as the self-resonant frequency becomes evident. Equation: (12) shows that when $Z_{ESL} == Z_C$, the capacitor is at its resonance point. At this frequency, the capacitor's impedance is determined solely by the ESR at that frequency. This frequency can be calculated by Equation: (13).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{13}$$

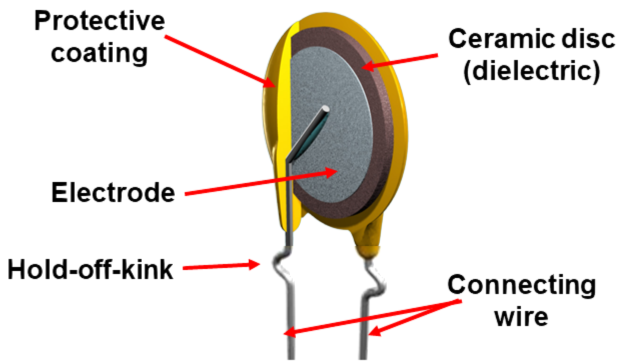

Figure 11: Dissipation Factor Plot

3.9 Dissipation Factor

Dissipation factor, otherwise known as the loss-tangent, is a measure of the energy stored to the energy dissipated per cycle. It is a measurement of the efficiency of the capacitor. The DF can be quantified through Equation: (14).

$$D = \frac{ESR}{Xc} \tag{14}$$

The loss tangent can be seen in Figure: 11. The greater the angle, the more efficient the capacitor will be.

3.10 Quality Factor

$$Q = \frac{1}{D} \tag{15}$$

The Quality Factor, Q, of a capacitor is found by taking the reciprocal of the dissipation factor, Equation: (15). It is defined as the ratio of the energy stored to the energy dissipated per cycle.

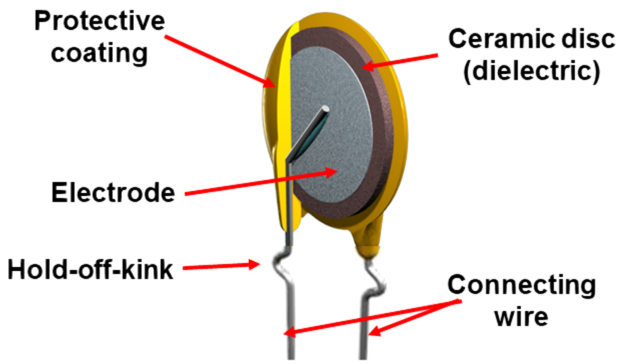

Figure 12: Dielectric Absorption

3.11 Insulation Resistance

Every capacitor will have some DC leakage resistance associated with it. This measurement is attenuated by the insulation resistance of the capacitor. A high insulation resistance in a capacitor will increase its ability to store charge. This characteristic is especially important in sample and hold circuits.

3.12 Dielectric Absorption

Dielectric Absorption, DA, in a capacitor is a characteristic which describes the unit's ability to "regenerate" a charge after being shorted to ground for a brief time.

As seen in Figure: 12, a capacitor can be modeled with multiple RC element, of a much greater time constant, in parallel with the bulk capacitance. When the main capacitor is shorted to ground, and then released, the other capacitors may not have released their energy. After several minutes, they can recharge the main capacitance to a significant portion of its original charge. This is why large valued electrolytic capacitors get shipped with a resistor across their terminals.

3.13 Old

This section will list and explain a large number of capacitor parameters. It will not deal with any analysis or measurement.

1. Impedance
2. Phase
3. Capacitance
4. Reactance
5. Equivalent Series Resistance (ESR)
6. Equivalent Series Inductance (ESI)
7. Leakage current
8. Dissipation factor
9. Quality factor
10. Dielectric absorption
11. Loss Tangent

4 Capacitor Modeling

This section will follow the capacitor parameters section and explain the aspects of modeling and show examples of how to corellate physical data to a theorectical model.

1. RC ladders

Input Scale	0 to +10V for 0 to full-scale
Input Impedance	1 MΩ
Accuracy	±0.2% of full scale
Update Rate	15 Hz
Output Slew Rate	<0.3s for 0 to full scale (full load)

Table 1: SRS PS350 External Voltage Control Characteristics

[24] [23]

5 Measurement Circuitry: Version 1

5.1 Overview

This section will describe version 1 of the circuitry proposed to measure the parameters needed to analyze a capacitor. It will present analytical and empirical assessments of each circuit section where feasible and applicable.

5.2 Protection

This subsection will explain the protection circuitry used to isolate parts of the circuit from the high DC voltage in the event of a failure.

5.3 DC Bias

The DC Bias circuitry will provide a controlled DC voltage from 0 to 500V. This voltage will be used to provide a DC bias for AC measurements, and to allow for charge/discharge measurements. A Stanford Research Supply PS350, 500VDC power supply will be used to generate the voltage. This supply will be controlled either manually or via its 0-10VDC external control input. Table: 1.

Actual measurements of the supply can be seen in Table: 2. As the table indicates,

Voltage In (V)	Voltage Out (V)	Absolute Error	Percent Error
.01	7	2	40%
.02	11	1	10%
.1	52	2	4%
.2	101	1	1%
1	505	2	0.4%

Table 2: SRS PS350 actual measured gain

Voltage Out (V)	RMS Ripple (V)	PP Ripple (V)
10	0.008	
50	0.010	
100	0.015	
500	0.066	

Table 3: SRS Noise over Range of output values

the supply does not exhibit reasonable control below 20mV of control signal (10V output). ¡—Need to include a noise or stability table over input voltages.—¿

The RMS and peak-to-peak ripple voltage for the same range of outputs are shown in Table: 3.

The block diagram in Figure: 14 and the circuit in Figure: 13 show the logic for programatically controlling the SRS supply. The AD7391, a 12-bit DAC, is used to generate the desired control voltage for the SRS supply. Using a 1.0V xxxxx, a precision external reference, the output of the DAC swings from 0-1V with a resolution of 244uV. This sets the SRS supply from 0-500V with a resolution of 122mV. These numbers are theoretical and will degrade from ideal due to the SRS's response to the control signal, the noise levels in the system, and various other factors, such as temperature.

The AD7391 has a buffered output with a $1k\Omega$ output drive capability (for this

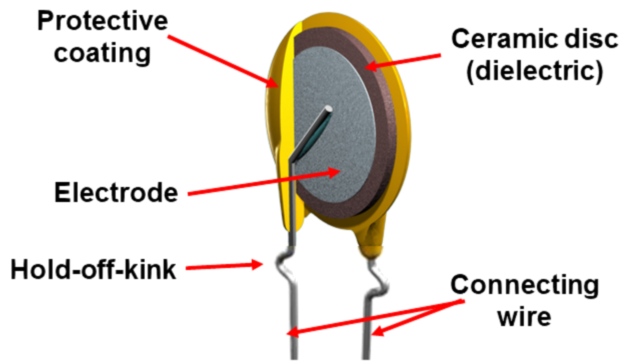

Figure 13: SRS DC Bias Supply Control Circuit

application). Since the SRS supply is rated at a $1M\Omega$ input impedance, the specs should allow the DAC to directly control the power supply. To be on the safe side, an in-line, optional buffer is added to the circuit.

The AD7391 is controlled via a SPI bus connected to a microcontroller. The speed of this interface is not important because the system will only every change the output value of the DAC in between tests, not while collecting data. The DAC also has a CLR input that forces the output to 0V. The $10k\Omega$ pull down resistor ensures that the output sets the SRS supply to 0V upon start up for safety reasons.

As an added safety precaution, the SRS supply has the ability to enter in a manual voltage and current limit. The voltage limit will be set by the user to the maximum voltage of the particular test at hand.

Error calculations:...

5.3.1 Control Limiter

This circuit section provides a set-point for the maximum allowed control signal to the SRS supply. It acts as a secondary safety limit. The primary limit being the SRS supply's front panel limit setting.

R802 and R805 provide a voltage divider; taking 5V down to 3V. R804 and R806

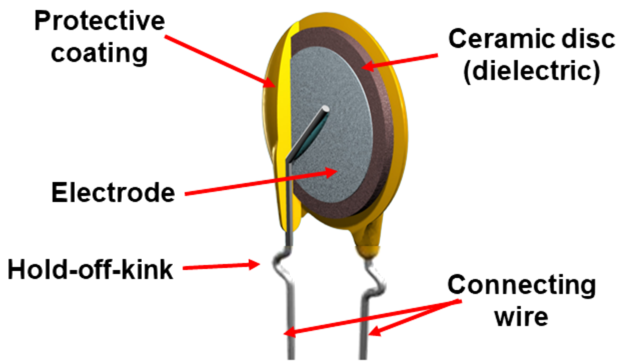

Figure 14: SRS Control Circuit Block Diagram

work with the potentiometer, R803, to provide a manual adjustment up to 3VDC. The diode in the feedback loop of U801 is known as a precision diode. [13, ch5.1] It limits

List of things to explain:

1. Super-diode
2. resolution of DAC
3. resolution of control
4. effect of noise on the output
5. logic for controlling the max control signal.
6. overvoltage shunt?
7. series resistor between last op amp and SRS

5.4 (Dis)Charge Circuitry

This subsection will explain the circuit used to (dis)charge the DUT and the circuit used to measure the current through the DUT.

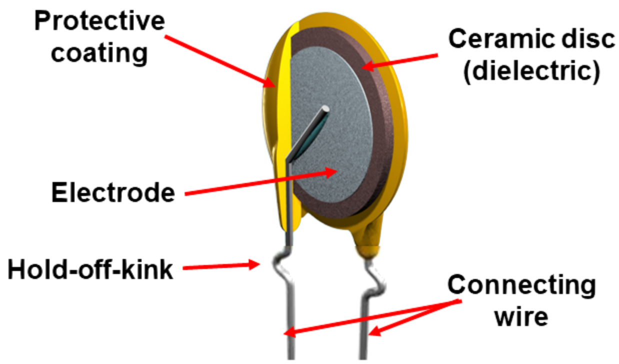

Figure 15: (Dis)(Charge) Block Diagram

The basic purpose of this section is to measure the charge/discharge curves of the DUT by stepping the input voltage and then measuring the current through the device over time.

The block diagram depicted in Figure: 15 shows how this section will function. There are three basic modes:

Charging: In this mode, the supply is set to the desired voltage and then stepped into the circuit with a relay. The input voltage sees a known resistor in series with the DUT to a virtual ground. The DUT will charge up to the input voltage according to its time constant. The virtual ground is made up of a transimpedance amplifier. It has the advantage of being able to measure on the low side of the DUT.

Discharging: With the Charging side disconnected, a relay can connect the discharging circuitry to ground through a series resistor. The current measurement circuitry performs the same function, but with the opposite polarity measurement.

Leakage: Once the DUT is charged to its full voltage, the steady state current can be measured over a much larger time period.

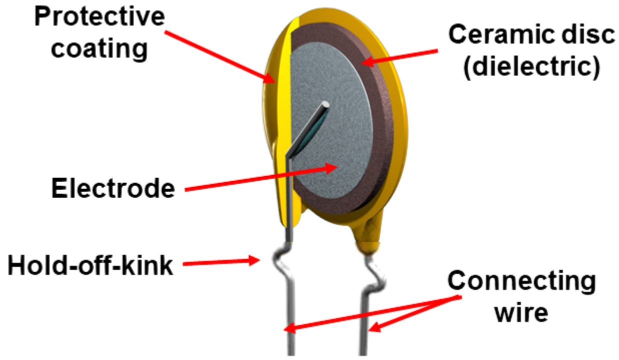

Figure 16: Relay Control Circuitry

5.4.1 Relay Control

Each relay is controlled with independent circuitry as shown in Figure: 16. The basic operation is that the input control signal (active high) switches either 5V or GND to the low side of the relay's coil. A ringback diode in series with a small valued resistor is in place to limit the coil's inductive spike while switching. Additionally there is a resistor + LED to indicate when an individual relay is active.

5.4.2 Transimpedance Amplifier

The transimpedance amplifier section is in place to provide a low side current measurement. It provides a

5.5 AC Signal Injection

This subsection will cover the circuitry and supporting tech needed to inject an AC signal onto the DUT.

5.6 Transformer

This subsection describes the equations and operation of the transformer used to inject the AC signal ont the DUT.

5.7 AC voltage Measurement

This subsection describes the AC voltage amplitude and phase measurements.

5.8 Rise and Fall Times

This subsection describes the circuitry used to mesaure the rise and fall times of the DUT.

6 Conclusion

This section will summerize the methodologies used to solve the stated problem.

7 Future Work

This section will describe the future work needed to be accomplished in order to complete and further the stated goals of this thesis. It will mostly focus on the practical circuitry implementation and other aspects needed to make it a viable tool.

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