

Effect of DC Bias on Effective Capacitance of MLCCs

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Rough Draft

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1. Introduction

Opening up any modern computer will reveal hundreds of electrical components, ranging from the minuscule resistors to large chips with hundreds of electrical contacts. Among these one shows up on nearly every circuit board. A multi-layer ceramic capacitor or MLCC is used in just about every circuit produced today. Both in precise high speed applications, such as on a CPU, and high power designs, like a DC-DC converter, they have a wide range of uses. Through their combination of ease of use in assembly, low cost, and small size, MLCCs have become an indispensable tool in circuit design.



Figure 1: MLCCs come in many shapes and sizes, with some as small as a grain of sand

Despite being mainly used in mass production of consumer products, MLCCs are simultaneously used in hobbyist designs. While nearly always coming in Surface Mount packages, though hole packages exist, making them easy to solder by hand. And while other types of capacitors exist, they do not offer the same characteristics.

1.1. Voltage, Current, and Resistance

To understand their function and why they are universally used, it is important to first understand the basic theory of how electricity flows. Voltage, a potential difference, causes current, the flow of electrons, through a conductor.

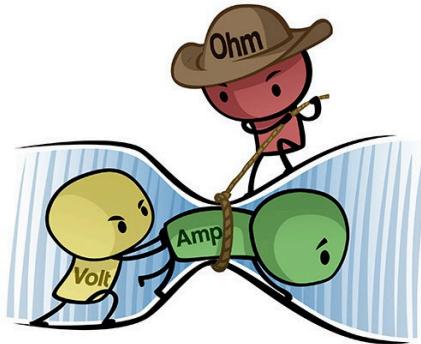


Figure 2: A popular cartoon representing voltage and amperage

When a voltage difference, such as from a battery, is applied across a conductor, current is allowed to flow unrestricted through that conductor. This is known as a short circuit. The amount of current flowing can be limited by using a resistor. A resistor is a component where the current flowing is directly proportional to the amount of voltage across the resistor. This relationship is shown in the following equation where V = voltage (measured in volts), I = current (measured in Amps), and R = Resistance (measured in ohms).

$$V = I \cdot R$$

This relationship is known as Ohm's Law. As an example, if a 5V battery is connected to a 100Ω resistor, the current can be found.

$$V = I \cdot R$$

$$5V = I \cdot 100\Omega$$

$$\frac{5V}{100\Omega} = I$$

$$0.02A = I$$

As seen above knowing any two variables of this equation allows solving for the third. The equation can be manipulated to solve for Resistance, $R = \frac{I}{V}$, or current, $I = \frac{V}{R}$.

1.2. Model of Capacitor

A capacitor is a device where the current flowing through is proportional to the rate of

change of voltage. That is, $I = C \frac{dv}{dt}$ where C is the capacitance in Farads. When a capacitor is connected to a constant current source the voltage across the capacitor will increase at a constant rate. Functionally, it is very similar to a battery in that it can be charged and then discharged.

This models an ideal capacitor, but real capacitors and especially MLCCs face non-idealities which change this model. One of the most important, yet often overlooked, ones in MLCCs is DC-bias. DC-bias causes the capacitance, C , of a capacitor to be reduced as a voltage is applied across the capacitor. This introduces a new curve, which is the capacitance versus voltage curve. Manufacturers of capacitors will provide this graph. An example of the DC Bias graph of standard capacitor is shown in Figure 3.

These curves have a domain of $0 < V < v_{\max}$ due to maximum ratings and capacitors not having directionality.

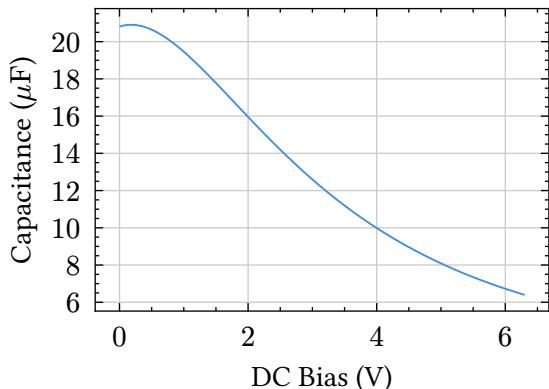


Figure 3: DC Bias of $22\mu\text{F}$ capacitor from Murata¹

Because Capacitance is in fact a function of voltage, $C = C(V)$, a more accurate model of a capacitor is $I = C(V) \frac{dv}{dt}$. This is important when there is large change in voltage across the capacitor.

1.3. Research Question

The effect of DC Bias is mainly used in AC analysis applications, such as for a bypass capacitor. In these applications, because the voltage does not make any large changes, it is

sufficient to put C as a constant, functionally making the capacitor a derated version of itself. This can not be done when a device is first turned on, and a MLCC goes from 0V to V_{on} , a large voltage change.

Often components will have an enable pin that will only allow the device to turn on when the voltage reaches a certain threshold. Meeting rigid timing requirements necessitates knowing how quickly the voltage across a capacitor will rise. This paper will attempt to find **the effect DC Bias has on the effective capacitance of a MLCC during device turn on**.

2. RC Formula

2.1. Applications

Creating the constant current source in Section 1.2 for a capacitor can be difficult, so instead a resistor, as mentioned in Section 1.1, can be used to limit voltage increasing across a capacitor. Resistors, similar to capacitors, are relatively cheap and come in small package sizes. Combining these two components creates a circuit often referred to as an RC Circuit. The diagram of this is shown in Figure 4.

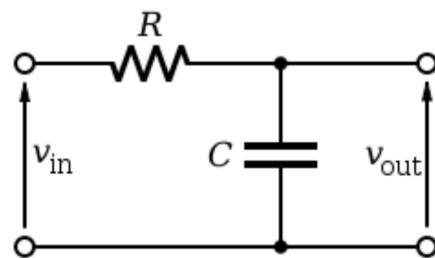


Figure 4: Schematic of RC Circuit

This circuit is often used to limit noise in a system in order to prevent unexpected behavior. Here it will be used to slow down the rise time of voltage across a capacitor.

By mathematically modelling this circuit, the below equations are generated.

$$V_R + V_C = V_{\text{on}} \rightarrow V_C = V_{\text{on}} - V_R$$

$$V_{\text{out}} = V_C = V_{\text{on}} - V_R$$

¹Part number GRM21BR60J226ME39L

Substituting in the formula from Section 1.1 for V_R we get:

$$V_{\text{out}} = V_{\text{on}} - IR$$

And finally using the equation for a capacitor from Section 1.2 to replace I :

$$V_{\text{out}} = V_{\text{on}} - RC \frac{dV}{dt}$$

The equation in this form isn't very helpful because it is not possible to easily input a time and get an output voltage. Because of this, the equation is almost always manipulated into the RC formula, shown below. This process is explained in Section 2.2.

$$V_{\text{out}}(t) = V_{\text{on}} \cdot \left(1 - e^{\frac{-t}{RC}}\right)$$

This equation allows us to get the output voltage with a specific time of an ideal capacitor.

2.2. Derivation

The formula in Section 2.1 can be derived using the following process.

3. Experiment

3.1. Overview

An experiment allows the greatest degree of accuracy in determining the behavior of a capacitor in the real-world but is also the costliest and most time consuming. If the appropriate component needs to be chosen from a large selection, than buying and testing them all is unrealistic.

Despite this shortcoming, an experiment is invaluable in that it will always provide the highest degree of accuracy to how a component will behave in the real world. Due to this, the results from this experiment will be the benchmark for the methods used in Section 4 and Section 5.

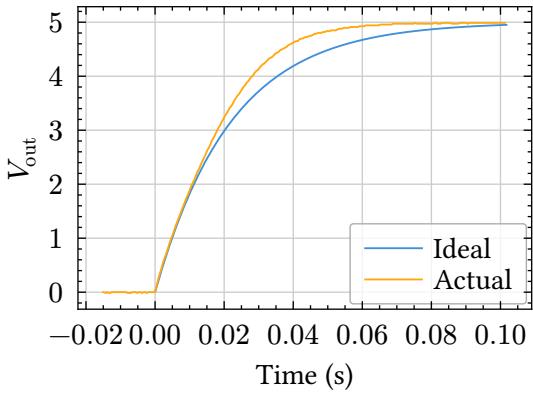
3.2. Set Up

A printed circuit board, designed for a RC circuit, was populated with a $1\text{k}\Omega$ resistor and a $22\mu\text{F}$ Capacitor with a rated voltage of 6.3V. The circuit board was then held in place with exposed positive and negative 22 wires. A power supply was set to 5V with no current limit and the negative side of the power supply and PCB were connected. A 10x oscilloscope probe with a ground spring was connected across the capacitor while another 10x probe was connected between the two power wires. The capacitor was discharged by shorting the two ends using metal tweezers. The positive side of the power supply was then put in

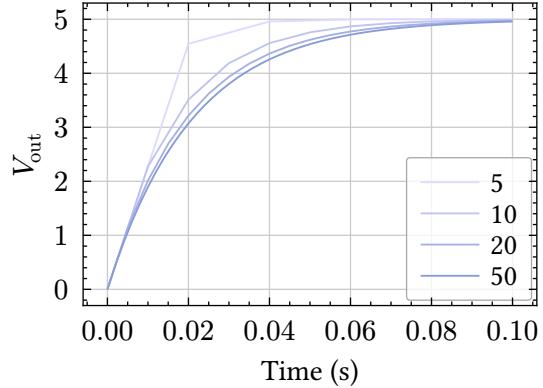
contact with the resistor side of the PCB and a waveform was obtained. This set up is depicted in. More details on the PCB and oscilloscope used can be found in Appendix A.

3.3. Results

As expected, the voltage rises faster than an ideal $22\mu\text{F}$ capacitor. A comparison is shown in the figure between an ideal $22\mu\text{F}$ capacitor and the real capacitor.



We can use this graph to approximate a RC value for the circuit. Because R is known we can find what the equivalent capacitance would be.



Using this script to generate the curves we are able to also change the capacitance with reference to voltage. Using the DC Bias curve from the manufacturer, the same from Section 1.2, we can use a linear function to approximate the capacitance based on voltage. The formula chosen was $C(V) = 22\mu\text{F}$. This approximation is shown in Figure 5.

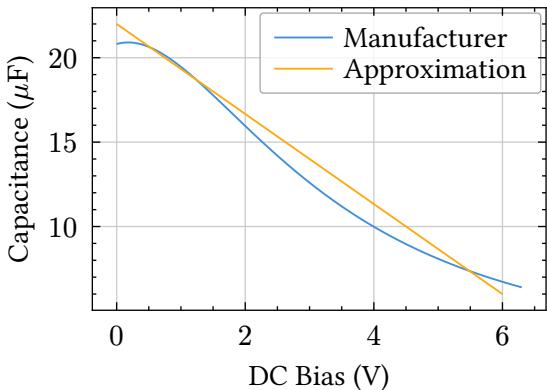


Figure 5: DC Bias of $22\mu\text{F}$ capacitor from Murata

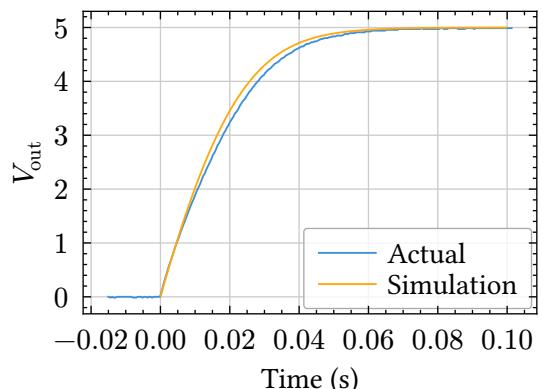
4. Simulation

4.1. Overview

The speed of modern computing has made simulation in a variety of situations useful. Due to the efficiency of processing repeated operations, computer software is perfect for circuit simulation. In this section, python, a modern programming language will be used to simulate the effect of DC Bias on the RC circuit. In the python code in Appendix B, small time steps can be used. In each time step the change in voltage across the capacitor is based on the current through the resistor for that amount of time. Making these time steps very small can lead to a very accurate result. The graph in figure shows five to fifty time steps.

4.2. Results

Using this approximation, a simulation is run using 200 time steps across a 100ms period. The curve obtained is compared with the actual, acquired from oscilloscope, in figure.



This appears to be much closer to the actual than what would be predicted for a $22\mu\text{F}$ capacitor. Here we can use the same process as in Section 3.3.

5. Deriving New Formula

5.1. Derivation

Using the same estimation we can substitute in for $C(V)$. Using a similar process as for the original RC formula we can find a new formula.

5.2. Results

The result of this formula is plotted. RC is found.

6. Comparison of Methods

The Simulation and derivation are likely very similar in results. They appear based on the experiment to better than a constant capacitance at either end (V_{max} or 0V)

7. Generalization

Compare capacitance vs. voltage of different types of capacitors (x5r, x7r, 0805, 0603)

Try to find a general formula that can fit this curve

Do five again but with a generalized formula

Compare to LTSPice and Experimental results

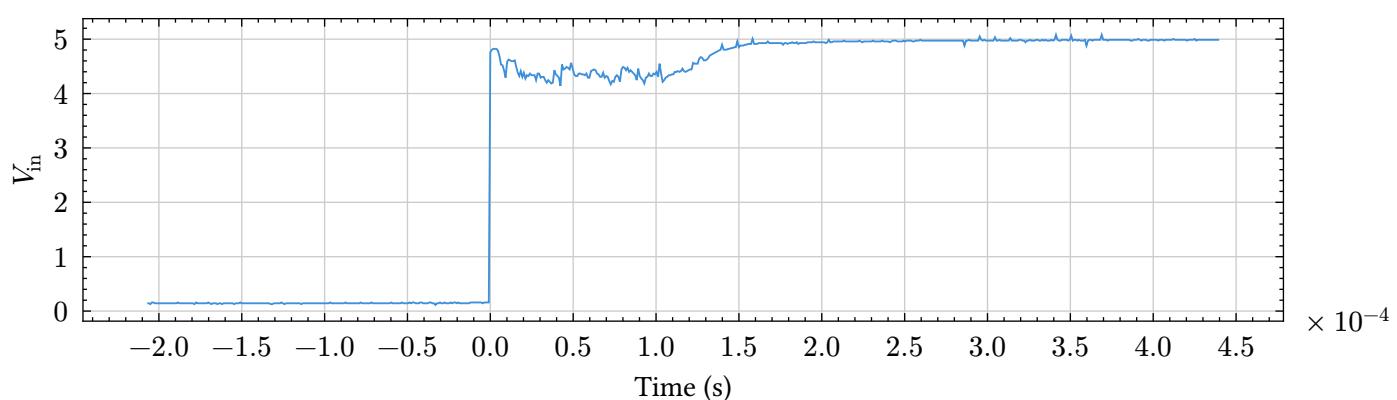
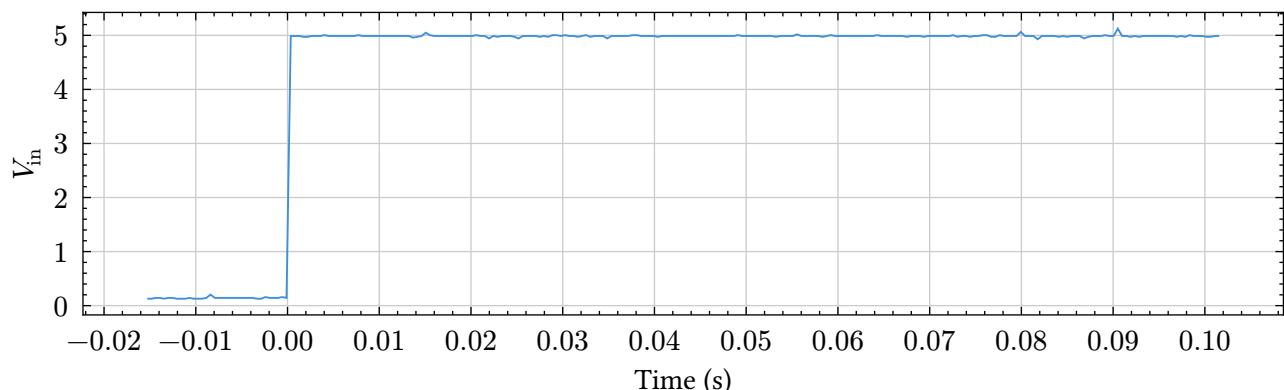
8. Conclusion

How this could be useful in my life and elsewhere

Why it might not be accurate (This focused on bulk capacitors which might not be as common for enable pins due to size, Model might not be accurate because capacitance might not immediately change with dc applied across the capacitor (maybe experiment with this with different resistor values and see if C from RC stays the same))

Something else?

A Waveforms



B Code

```
1 import csv
2
3 file = open("data/sim-50.csv", mode= "w", newline = "")
4 writer = csv.writer(file)
5
6 #1k ohm
7 R = 1e3
8 #5V
9 V = 5
10 #22uf
11 C = 22e-6
12
13 #100ms
14 end = 0.1
15 steps = 50
16 dt = end/steps
17 t = 0
18
19 #voltage across capacitor
20 out = 0
21
22 writer.writerow([0, 0])
23
24 #DC Bias capacitor
25 for i in range(steps):
26     #Voltage and thus current across resistor during this step
27     Vr = V-out
28     I = Vr/R
29
30     #Linear approximation of capacitance due to DC bias
31     C_bias = 22e-6 - (2.33e-6 * out)
32
33     #Based on current and amount of time, increment voltage
34     dv = (I*dt)/C
35     out = out + dv
36
37     #record result
38     t = t + dt
39     writer.writerow([t, out])
40
41
42
43 file.close()
```