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EXPLORING THE CONCEPT OF SELF OSCILLATING PHOTOVOLTAICS

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ABSTRACT

Solar cell technology has the potential to be highly competitive in the energy market, as the Sun produces more than enough energy daily to offset humanity's yearly needs. However, in order for it to become competitive, the costs associated with producing solar cells must decrease. Researchers have been looking at ways to increase the efficiency of solar cells, thus increasing the usable energy from a single cell, as well as looking at ways to gather solar energy from larger areas, known as solar concentration. There is, though, another large cost associated with solar cell production and usage. This is the cost to convert DC power to usable AC power, which makes the energy from these cells usable.

Since most energy used in the United States is in the form of AC power and solar cells produce DC power, expensive inverters are needed to convert the energy. This thesis aims to find a new way to perform this conversion using memristive devices in a relaxation oscillation circuit. Memristors are two terminal circuit elements whose resistance depends on the previous applied voltage. Using this technology along with a relaxation oscillation circuit, a circuit model was developed along with desired hysteretic I-V characteristics. This model was then implemented in MATLAB to test for working parameters that would satisfy the conditions.

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Chapter 1

Introduction

The photovoltaic effect, first discovered by the French physicist Antoine-Cesar Becquerel in 1839, is the basis of how solar cells operate. He observed that a voltage was created when the electrode was exposed to light. Charles Fritts further explored this phenomenon in 1883. He made the first "true solar cell" using the semiconductor selenium and a thin layer of gold[1]. However, his cell had an efficiency of under 1%. In 1954, Daryl Chapin, Calvin Fuller and Gerald Pearson of Bell Labs created the first efficient solar cell, with a 6% efficient silicon p-n junction[2]. They were able to power a toy windmill and radio with this cell. In 1958, a US satellite, Vanguard 1, was sent into spaced equipped with solar panels to power its radios. This began the investment into the solar energy industry.

Due to global climate change and the rising costs in oil and other carbon "fossil" fuels, the interest in renewable energy has been on the rise. Solar energy is one of the most promising of the renewable energy options (including solar, hydroelectric, wind, nuclear, biomass, geothermal, etc.) since it does not require moving parts, has small environmental impact and could potentially create large amounts of power if efficient. Figure 1 below shows a comparison of the world's current *yearly* energy consumption (red) verses the amount of energy available from the sun *daily* (red).
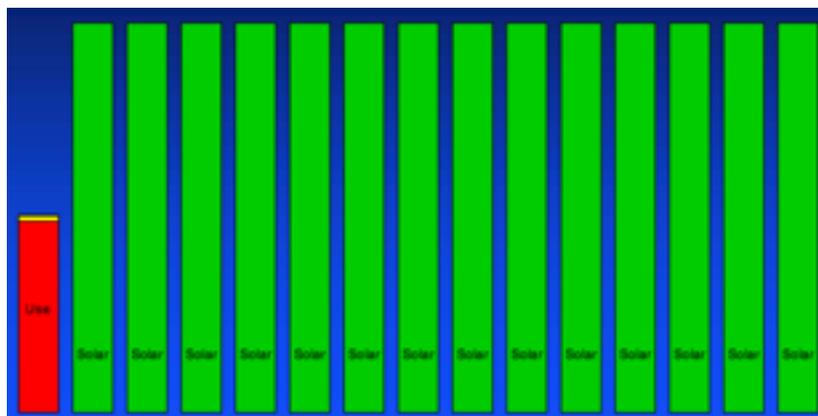
Figure 1. Yearly Energy Consumption vs. Daily Solar Energy

There are several ways to make solar energy a more viable energy option. One way is to increase the efficiency of solar cells. This will increase the amount of usable energy for any given area of solar cell. Another method would be to increase the area where the sunlight is collected, known as solar concentration.

Traditional or "first generation" solar cells are single-crystalline silicon single junction devices that make up around 85% of the industry today. Unfortunately, these solar cells are expensive, bulky and difficult to create. They also come with a max energy conversion efficiency between 31% and 41% due to fundamental thermodynamics, known as Shockley-Queisser efficiency limit[4]. "Second generation" cells are thin films of amorphous silicon and other semiconductor materials. While these are cheaper than first generation cells, they are also less efficient, due to non-radiative recombination losses and lower film quality. "Third generation" cells aim to both decrease the production costs as well as increase efficiency in solar energy. The current cost of solar energy is $1/Watt and these third generation cells strive to decrease this to less than $0.20/Watt[4]. Third generation cells try to combine the advantages of the previous two generations. The new technologies being looked into include multi-junction cells, intermediate band cells, hot carrier cells, and by looking at new materials such as quantum dots/wells.

Solar concentrators use Fresnel lenses to bend and focus rays of sunlight towards one specific spot. By placing a solar concentrator on a solar cell, the cell becomes more efficient because it now has more focused light coming in. There are currently two main methods to increase solar concentration, one uses parabolic trough mirrors and the other mirror arrays. Unfortunately these are very large and complicated and used only in industrial power plants. A newer concentrator, called luminescent solar concentrators (LSCs), is a glass or plastic plate coated with a dye, called luminophores. The luminophores absorb solar light in the material and then directs the energy in random directions. The light is then absorbed by solar cells on the edges of the plate[5,6]. LSCs help increase the effective area and thus make each solar cell more efficient and cheaper.

Another aspect not often looked at is the conversion from direct current to alternating current using inverters. Solar cells produce direct current (DC), but most appliances run on alternating current (AC), so a conversion must take place. If this step could be cut out, the cost of using solar cells for energy would decrease, which is the main focus of this thesis.

Chapter 2

Literature Review

2.1 Background Physics

The amount of energy from a photon of light (Eph) can be determined from its frequency, v, or wavelength, λ by the following equation:

$$E_{ph} = hv = \frac{hc}{\lambda}$$

where h is Planks constant and c is the speed of light. Semiconductors have what is called a band gap, which is the energy separation between its valence band and conduction band. If a semiconductor gains energy greater than or equal to this band gap energy, electrons from the valence band become excited and jump into the conduction band. When this happens, the semiconductor material now becomes conductive[7].

For a photovoltaic device, photons in incident light interact with the electrons in a semiconductor when they have energy greater or equal to the band gap energy. The photon is absorbed when it interacts with an electron that can transition to another excited state. As the photon is absorbed, what is called a hole is left behind. As electrons and holes are excited near the p-n junction, they start to move due to the built-in electric field, known as the photovoltaic effect. This creates a potential difference (voltage) or a direct current, which delivers a power to an external load.

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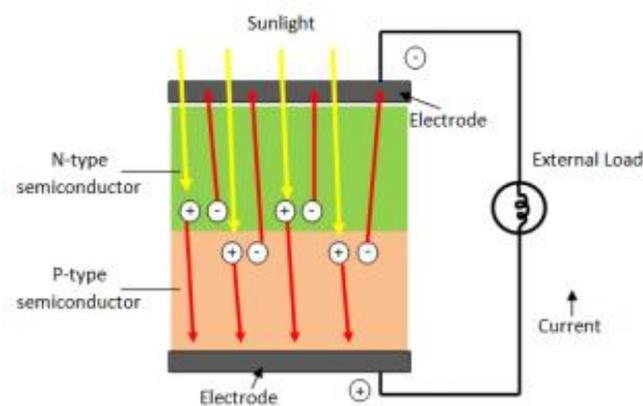
Figure 2. Photovoltaic Cell

To make this effect happen, p-n junctions are required. P-n junctions are created when a semiconductor is doped in two different layers. A material is doped by adding atoms differing in makeup than the original material. In silicon, for instance, to create free electrons, Phosphorus atoms are usually introduced, since they have more valence electrons. This is called n-type doping. To create free holes, Boron atoms can be introduced since they have fewer valence electrons. This is called p-type doping. By joining two layers, one with n-type and one with p-type, the free electrons in the n-type layer will diffuse into the holes in the p-type layer. This creates an electric field that creates an equilibrium. This equilibrium causes the drift of electrons and holes from the electric field to equal the natural diffusion that occurs. When photons are added to this, the equilibrium is disturbed and the photon carriers drift across the p-n junction, which creates a direct current.

2.2 Inverters

When solar cells produce electricity, it is in the form of direct current (DC). DC power is that of your typical battery, used for charging phones and simple appliances. However, many of the appliances used today are designed to work with alternating current (AC) power, which is the type of electricity that comes out of a wall socket in your house. This is because in the 19th century, Nikola Tesla and Thomas Edison debated over whether DC or AC systems would be better or safer. Although Edison tried to convince that AC was dangerous, in the end Tesla's AC systems won, and today, most of our world runs on AC power[8]. Thus, in order to make solar cells useful for home use, a conversion from DC to AC is required. This is done through a DC-to-AC inverter.

DC is the continuous flow of electrons due to a change in potential from one end of a wire or field to another. AC on the other hand, switches the direction of the flow of electrons (changes polarity) at a constant rate, usually 50-60 times a second (or a frequency of 50-60 Hz). DC usually has a lower voltage output than AC. For them to be useful, inverters must increase the DC voltage and then change it to AC[9].

There are several different types of inverters available. Early inverters were mechanical, using electromagnetic switches to turn on and off at very high speeds. Current flows from one end of the circuit until it hits a magnet. Once the magnet is activated, it pulls a wire on a spring. This wire then comes in contact with the circuit, reversing the flow of current. Once the magnet is released, the spring releases the wire and the current again switches direction. This process then continues to repeat[9]. These inverters usually create a square-wave output, which can only be used for certain electrical appliances[8].

Typical AC looks more like a sine-wave that gradually changes from one direction to another. Modern inverters are electric inverters, which can create a smoother output using oscillator circuits. These inverters use transistors, inductors and capacitors to make the output current rise and fall gradually, as these components are able to filter and store energy. Unfortunately in this process, some power is lost in the form of heat. Inverter efficiencies vary based on the amount of power being used. They can range from just over 50% to over 90%, with a typical solar inverter being around 95% efficient[10].

In order to get a pure sine-wave output, an oscillator must be used. Simple oscillators such as a Wien Bridge with FET can be used and the output remains stable due to the feedback. Using a transformer, the output can then be amplified by increasing the voltage. Other inverters use microcontrollers and their pulse width modulation operation to create a pure output wave[10]. However, as each of these inverters become more accurate, they also get increasingly more expensive.
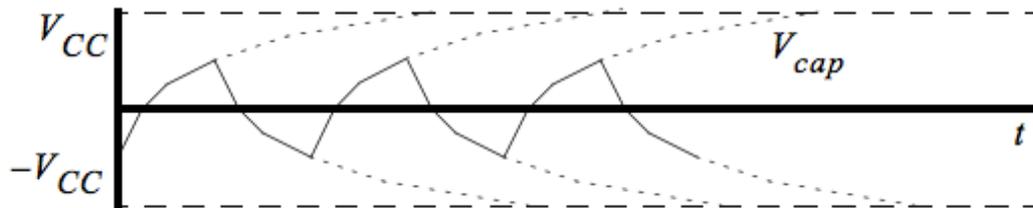
2.3 Relaxation Oscillation

Self oscillating systems take an input from a power source with no periodicity and create an output with periodic motion. The difference between self oscillations and forced oscillations is that an outside force must be continually applied to the forced oscillation to keep the periodic motion going. In forced oscillations, if the external force is removed, the periodic motion will decrease until it ceases motion (think of a swing that stops getting pushed)[11]. Self oscillators, however, are controlled by the oscillations themselves. Energy to reach the resonant frequency is caused by negative damping[12]. There are many familiar things that are self oscillators, such as "the heartbeat, the firing of neurons, ocean waves, turbines, clocks, many musical instruments (including the human voice), heat engines and lasers[12]." In this thesis, the goal is to take a steady power source (the DC solar cell) and create a maintained periodicity (AC power). To do this we will take a closer look at a specific type of self-oscillator called relaxation oscillators.

The simplest relaxation oscillators are RC circuits. In these, the voltage switches between two fixed values as the capacitor charges and discharges once reaching a threshold. Relaxation oscillators receive their name because the output 'relaxes' towards a fixed value with a periodicity determined by the RC time constant. Two simple examples of relaxation oscillators and an example of a relaxation oscillator output are shown in the figures below.
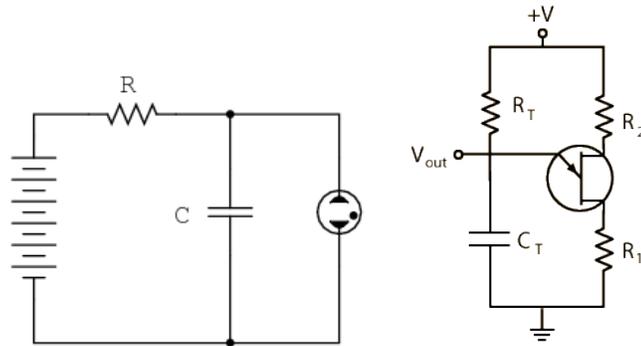
Figure 3. Left: A simple relaxation oscillator using only a capacitor and resistor. Right: A slightly more complex relaxation oscillator using a transistor along with the capacitor and resistors

Figure 4. Output Voltage for a Relaxation Oscillator

Self-oscillation was experimentally being observed since the late 19th century, with G. B. Airy in 1830 being the first to look at the concept of self-oscillation, where "he characterized the vibration of the human vocal chords as a form of 'perpetual motion compatible with the laws of Newtonian physics.'"[12] Later, in 1880, French engineer Jean-Marie-Anatole Gerard-Lescuyer observed a switching of current direction phenomenon in his research at the manufacture of electrical generators. He noticed that this reciprocating motion occurred at constant periodic intervals. Gerard-Lescuyer describes it as follows:

> "As soon as the circuit is closed the magnetoelectrical machine begins to move; it tends to take a regulated velocity in accordance with the intensity of the current by which it is excited; but suddenly it slackens its speed, stops, and start again in the opposite direction, to stop again and rotate in the same direction as before. In

a word, it receives a regular reciprocating motion which lasts as long as the current that produces it."[13]

The following four self-oscillating systems all show relaxation oscillation behavior 1: series dynamo machine conducted by Gerard-Lescuyer (1880) 2: the musical arc discovered by Duddell (1901) and investigated by Blondel (1905), 3: the triode invented by de Forest (1907), and 4: the multivibrator elaborated by Abraham and Bloch (1917). Poincare (1908 musical arc), Janet (1919 series dynamo machine) and Blondel (1919 triode) all came up with a differential equation to describe self-oscillating systems. Janet later realized that all three of their systems could be derived from the same equation.

By the 60's, the Dutch electrical engineer and physicist Balthasar van der Pol was well known as a radio scientist and a leader in nonlinear circuits. British mathematician states "his work formed the basis of much of the modern theory of nonlinear oscillations […] In his paper, on "Relaxation-Oscillations" van der Pol was the first to discuss oscillations which are *not* nearly linear."[14] Van der Pol is often associated with being the discoverer of relaxation oscillations with the solution to his triode circuit equation in 1922[15]. Aubin and Dahan-Dalmedico explain this discovery as follows.

> "By simplifying the equation for the amplitude of an oscillating current driven by a triode, van der Pol has exhibited an example of a dissipative equation without forcing which exhibited sustained spontaneous oscillations:
>
> $$v'' - e(1 - v^2)v' + v = 0$$
>
> In 1926, when he started to investigate its behavior for large values of e (where in fact the original technical problem required it to be smaller than 1), van der Pol disclosed the theory of relaxation oscillation."

Then, in 1926, van der Pol proposed his generic dimensionless equation that described

the dynamical properties of all three of Poincare, Janet and Blondel's systems. Van der Pol took

these experiments and created the concept of relaxation oscillations. This led to van der Pol's

oscillator, an oscillator with non-linear damping, which is governed by the van der Pol equation,

which is shown below.

$$y'' - \mu(1 - y^2)y' + y = 0$$

As the nonlinear damping parameter, μ, value is varied, the limit cycle starts as a circle

with $\mu = 0$ and sharpens as μ is increased. As μ increases the oscillation period changes. This is

shown in the figure below.
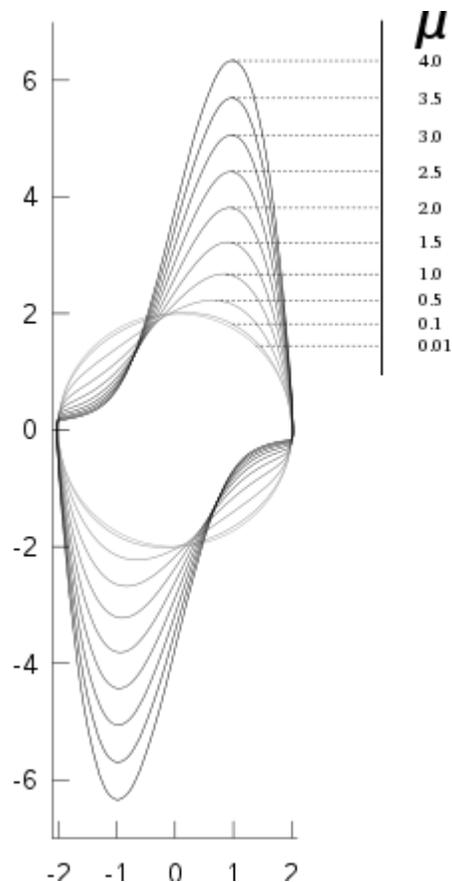
Figure 5. Varying μ Values (source: Wikipedia)

Since the introduction of the van der Pol equation in the 1920's, relaxation oscillators have been used in a variety of physics, electronics, biology, neurology, sociology and economics applications.[16] Van der Pol was interested in the range of heart dynamics stability and used his equations to build models of the heart to study these ranges. His equation has also even been used to study seismology by creating models of geological fault line interactions. The nonlinear relaxation oscillator acts as the energy stored up before an earthquake erupts. Just like an earthquake, the relaxation oscillator builds up to the threshold level until suddenly it discharges. By adding complexity to a simple relaxation oscillator, seismologist can add in parameters to simulate different external factors on an earthquake to study them better[17]. In this thesis, relaxation oscillators will be incorporated with resistive switching materials to try to create a self oscillating sinusoidal output from a constant input.

2.4 Resistive Switching

In order to make these oscillations, we will be trying to create a circuit using a resistive switching device, called memristors. Memristors are called the missing passive circuit element[18]. They are "missing" because they belong in the same category as capacitors (discovered in 1745), resistors (1827) and inductors (1831) all of which were discovered almost 150 years prior[19, 20]. These circuit elements relate the four circuit quantities: charge, current, voltage and magnetic flux. Memristors are two terminal circuit elements that relate charge moving through a circuit and magnetic flux surrounded by the circuit. Memristors are memory resistors, whose resistance depends on a complete past history of the memristor current (voltage). Once the voltage or current with respect to time is specified, the memristor behaves like a linear time-varying resistor. Memristors react to the past voltages. Strong E-fields or currents cause the dielectric within the memristor to change resistance.

In his 1971 paper, Leon Chua discovered the memristor by realizing there had to be another element. It was shown that memristors could not be built using the other three elements, thus declaring that it is fundamental[18]. The resistance of the device depends on the magnitude and the polarity of the voltage applied along with how long the voltage is applied. Once this voltage is removed, the memristor's resistance value remains constant to the value it had immediately prior to the voltage being removed. A memristor can be described as "a pipe that changes diameter with the amount and direction of water that flows through it[19]." Since the resistance changes based on the applied voltage, the I-V characteristic curves for memristors are hysteretic. The top image in the figure below is the original "pinched-hysteresis loops[18]" graph that Leon Chua proposed for the memristor's behavior. The bottom image is R. Stanley Williams's experimental result, which he called "bow ties"[21].
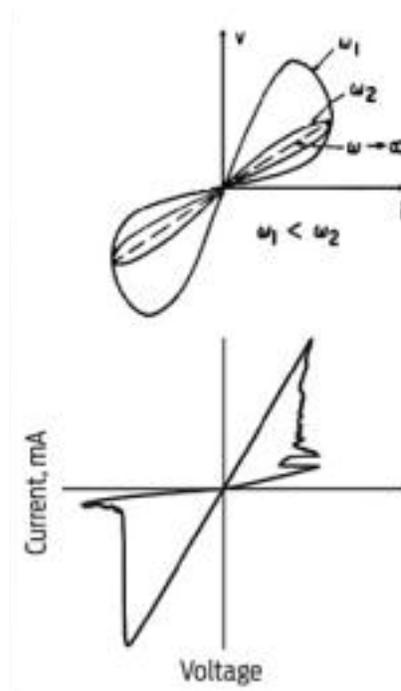
Figure 6. Top: Chua's Proposed Curve. Bottom: William's Experimental Curve[21]

In 2008 Williams, a scientist at Hewlett-Packard Labs, and his lab group were the first to put Chua's 40 year old theories into practice by creating a physical memristive device out of titanium oxide. For the past 50+ years, the semiconductor industry has relied on Moore's Law of shrinking transistors to increase technological speed. However, at some point, this will have to end and the development of new electronics will need a new direction. Williams suggests that memristors could be this next big step since they remember their history[19]. Even after the applied voltage is removed, the memristor has the ability to remember its last resistance. If a voltage is then reapplied, the memristor returns to this value no matter how much time passed between it being turned off and on again. This could be huge for computer memory. Imaging being able to remove the battery from your computer, without saving or quitting any applications, and when you plug the battery back in the computer turns on just where you left everything. This is one potential future for computers built with memristors.

One example of this memristive phenomenon is in TiO_2 and TiO_{2-x}[18]. The key to the switching voltage is the bilayer of the two different TiO_2 species, since TiO_2 is insulating and TiO_{2-x} is conductive. When a positive voltage is applied, the device turns on and when a negative voltage is applied, it turns off. As a positive voltage is applied to the top electrode, the oxygen vacancies are repelled from the TiO_{2-x} layer to the pure TiO_2 layer. This, in turn, makes the TiO_2 layer turn into TiO_{2-x} and is now conductive, thus turning the device on. In contrast, when applying a negative voltage, the vacancies are attracted up towards the TiO_2 layer. The added thickness to the TiO_2 layer turns the device off. This all creates the memristance as the electrons and charged dopants are forced to move between the layers, creating different resistances, when different voltages are applied.

Another material currently being researched for memristive behavior is VO_2[22/23]. VO_2 is "a traditional binary compound with different polymorphs" meaning it can exist in more than one form[22]." It is this characteristic that allows VO_2 to switch conductance from an insulator to metal. It has an insulator-to-metal phase transition (IMT) that occurs at room temperature. An applied current, e-field, and photoexcitation all have the ability to control this transition in VO_2. Four orders of magnitude change in the conductivity have been observed in the IMT of VO_2[22].

The role of the memristor in this thesis would be to act as a varying resistance depending on the applied voltage. A basic memristor would change between a conductive or ON state and a resistive or OFF state. We would want to choose a material that could allow the switching between these two states to be continuous and thus creating in-between states. In the basic simulation for this study, we will begin with two states and attempt to work up to an infinite number of states, or a continuously changing resistive device.

Chapter 3

Simulation

The goal of this thesis is to create a self oscillating circuit using a memristive (resistive switching) element, which will switch resistances based on the voltage applied. If parameters can be selected to make the simulation in MATLAB create the desired output IV curve, then looking into actual materials with these characteristics will take place. The basic circuit used for this simulation is the solar cell modeled as a voltage source, a capacitor and memristor in parallel, all in series with a series resistor (see figure below). The resulting characteristic equation for this circuit is also shown below:
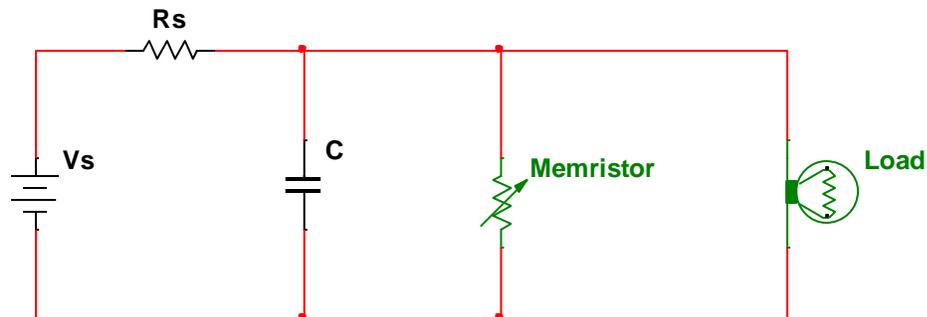
Figure 7 Multisim Depiction of Desired Circuit

$$\frac{V - V_s}{R} + C\frac{V_n - V_{n-1}}{\Delta t} + \frac{V}{M} = 0$$

where V is the voltage across the memristive element, V_s is the voltage source, Rs is the series resistance, C is the capacitance, and M is the memristive resistance. The general solution to this equation is:

$$V = V_s\left(1 - e^{-\frac{t}{RC}}\right), where\ R = R_s||M$$

However, as we move along the IV curve, this solution changes. This will be discussed further later on.

Since this is to be modeled in MATLAB the differential will be expressed in discrete time as $\Delta V/\Delta t$, giving the following equation:

$$\frac{(V - V_o)}{R_s} + \frac{C(V_n - V_{n-1})}{\Delta t} + \frac{V}{M} = 0$$

The solution to this equation is:

$$V_n = \frac{\Delta t M R_s}{(M\Delta t + CR_sM + R_s\Delta t)}\left(\frac{V_s}{R_s} + \frac{CV_{n-1}}{\Delta t}\right)$$

As the resistance across the memristor changes, the voltage across the capacitor is observed. As stated above in the Literature Review, many memristive devices exhibit hysteretic characteristics. In order to have the circuit oscillate, a hysteretic I-V curve for the circuit is also desired. The desired characteristics of the curve are shown in Figure 9.

To begin simulating this circuit, first only two different R values were chosen. This created the desired switching in voltage. Once the voltage reached a certain value, the resistance of the memristive element would change, thus causing the voltage to begin to decrease. However, with only using two resistances, this created a jump in current when the device switched, which is not realistic. The I-V, I-t, and V-t graphs for this circuit are shown below in Figure 8. For the sake of this simulation, arbitrary values for R_1, R_2, R_s, C, V_s and Δt were chosen. As long as the ratio of these parameters is the same, this circuit will produce the desired output. Changing the capacitance will only change the frequency.

To create the MATLAB model for this circuit, the conditions for when the memristive resistance was high or low had to be analyzed. For it to be a higher resistance, the current voltage had to be higher than the previous voltage and the voltage had to be lower than the switching

voltage. Once the voltage reached the high switching voltage (capacitor charging) and the

previous resistance was high, then the memristor would switch to a lower resistance, which will

then allow the capacitor to discharge. To stay on the lower resistance curve, the current voltage

had to be lower than the previous voltage and above the low switching voltage. Once it reached

the low switching voltage, the resistance switches back to the higher resistance. As this process

continues, the circuit oscillates between the two resistances, charging and discharging the

capacitor at some constant rate.
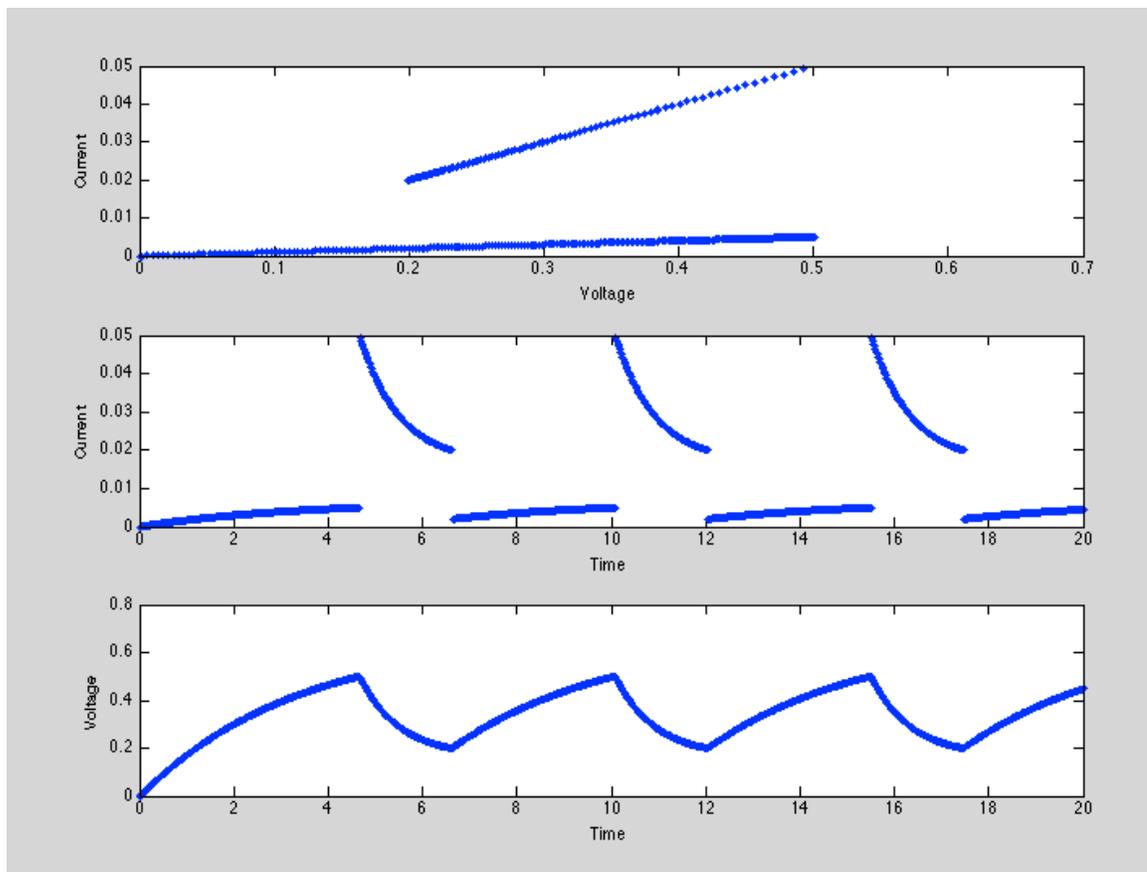
Figure 8. Simulated Results with Two Resistance Values

The goal is to add more resistances in the simulation causing the current to become

continuous and by adjusting the parameters, causing it to oscillate at a desired frequency. The

goal in this simulation is to have four resistances to create the desired I-V-characteristics as seen

in the figure below. In reality, the resistance will slowly change in response to infinitesimal changes in voltage.
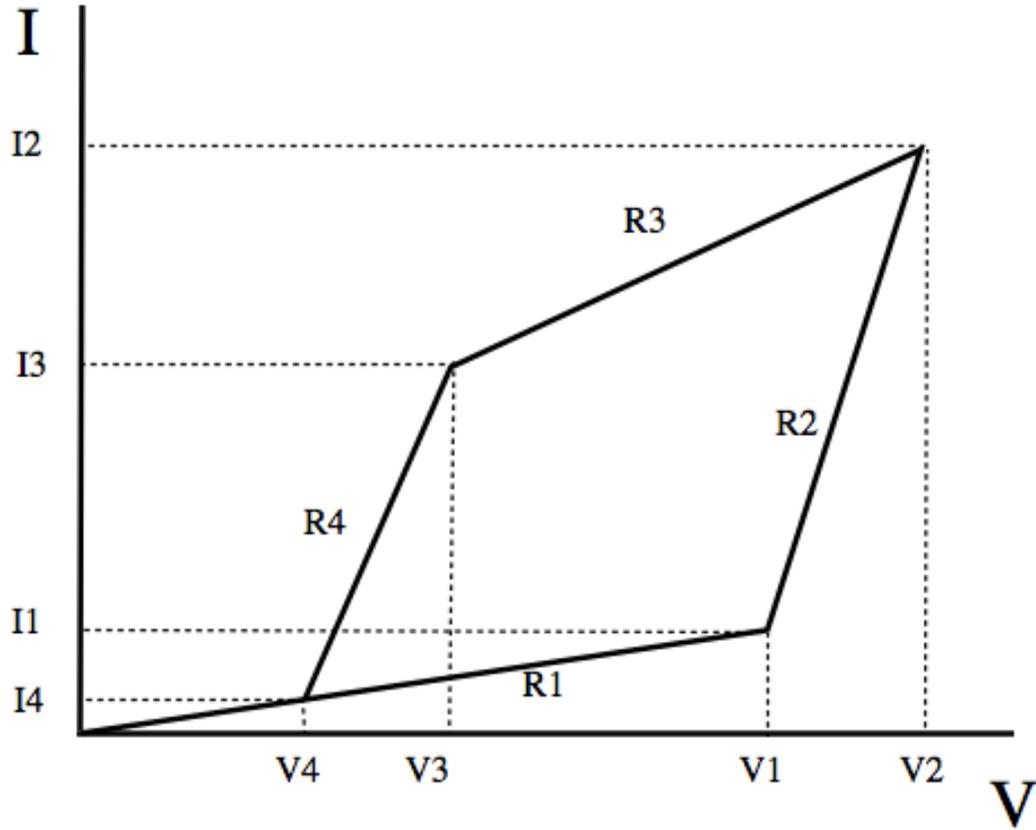
Figure 9. Desired IV Curve for 4 Resistance Circuit

Using the figure above and the circuit from Figure 7, we can determine the solutions to the general equation along each of the four curves: R1, R2, R3, and R4. The solutions are as follows:

$$\text{R1 curve: } V_1 = V_0\left(1 - e^{-\frac{t}{RC}}\right), 0 < t < t_1$$

$$\text{R2 curve: } V_2 = V_1 e^{-\frac{t-t_1}{R_2'C}} + R_2'\left(\frac{V_0}{R_s} + K_2\right)\left[1 - e^{\frac{-(t-t_1)}{R_2'C}}\right], \quad t_1 < t < t_2$$

$$\text{R3 curve: } V_3 = V_2 e^{-\frac{t-t_2}{R_3'C}} + R_3'\left(\frac{V_0}{R_s} - K_3\right)\left[1 - e^{\frac{-(t-t_2)}{R_3'C}}\right], \quad t_2 < t < t_3$$

$$\text{R4 curve: } V_4 = V_3 e^{-\frac{t-t_3}{R_4'C}} + R_4'\left(\frac{V_0}{R_S} + K_4\right)\left[1 - e^{\frac{-(t-t_3)}{R_3'C}}\right]$$

where $R_1' = \frac{R_1 R_S}{R_1 + R_S}$, $R_2' = \frac{R_2 R_S}{R_2 + R_S}$, $R_3' = \frac{R_3 R_S}{R_3 + R_S}$, $R_4' = \frac{R_4 R_S}{R_4 + R_S}$. (Note V$_1$-V$_4 \neq$ V1-V4. The Voltages in the

previous equations are the voltage at time t along the curve in Figure 8. V1-V4 are the switching voltages)

The K values are the offset values to allow the curves to all connect, which will keep the current

continuous as it goes around the path.

The first step to finding parameters that will fit this curve is to determine where each

segment wants to go as time goes to infinity. This is done by setting t=∞ in each of the four

equations above. This gives:

As t→∞

V$_1$: wants to go to V$_0$

$$V_2: R_2'\left(\frac{V_0}{R_S} + K_2\right), \quad V_2 > V_1$$

$$V_3: R_3'\left(\frac{V_0}{R_S} + K_3\right), \quad K_3 \leq I_2 \text{ and } V_3 < V_1$$

$$V_3: R_4'\left(\frac{V_0}{R_S} - K_4\right), \quad V_4 \text{ very small}$$

We will also look at the line equations for each of them and try to determine R and K

values that will satisfy the desired curve. The line equations for each I$_x$ and V$_x$ point are:

$$I_1 = \frac{V_1}{R_1} \qquad\qquad I_1 = \frac{V_1}{R_2} + K_2$$

$$I_2 = \frac{V_2}{R_2} + K_2 \qquad\qquad I_2 = \frac{V_2}{R_2} + K_3, \text{want } K_3 < I_2 \text{and } K_3 > 0$$

$$I_3 = \frac{V_3}{R_3} + K_3 \qquad\qquad I_3 = \frac{V_3}{R_4} + K_4$$

$$I_4 = \frac{V_4}{R_4} + K_4 \qquad\qquad I_4 = \frac{V_4}{R_1}$$

In order to satisfy the R4 curve, we know $R_4' \left(\frac{V_0}{R_s} + K_4 \right)$ has to be less than V_4, thus we

obtain $K_4 \geq -\frac{V_4}{R_4'} + \frac{V_0}{R_s}$. We can substitute this into our I4 equation for K4. Since we have two

equations for each point (since at each point two lines intersect), we should be able to work our

way to equations for I_1, I_2, I_3, and I_4 without K values. In the results section, we will go through

one example of a solution for these.

Looking at the curve, we can also find other conditions that must be satisfied to create the

desired results. These vary from what the K values need to be to what the switching voltages need

to be. The following are these conditions:

- $R_4'(V_0/R_s - K_4) < V4 < 0$ - $R_2'(V_0/R_s + K_2) > V2$

- $R_3'(V_0/R_s - K_3) < V3$ - $K_3 < I_2$

- $K_2 < 0$ - $K_3 > 0$

- $K_4 < 0$ - $V2 > V1$

- $V3 < V1$ - All currents are positive

- $V2 > V1 > V3 > V4$

Chapter 4

Results

Using the line equations obtained in the Simulation section, an equation for I_1 was

obtained using only R and V values. We start with the condition that $R_4'\left(\frac{V_0}{R_S} + K_4\right) < V_4$, which

gives us $K_4 \geq -\frac{V_4}{R_4'} + \frac{V_0}{R_S}$. From here we can use this equation for our K_4 value. Plugging this into

our I_4 equations gives: $I_4 = \frac{V_4}{R_4} + \left(\frac{V_0}{R_S} - \frac{V_4}{R_4'}\right)$. We then proceed to use the two equations for each

line found in the Simulation section. We end up with the following results (All V values are

switching voltages):

$$I_3 = \frac{V_3}{R_4} + \left(\frac{V_0}{R_S} - \frac{V_4}{R_4'}\right) = \frac{V_3}{R_3} + K_3$$

$$K_3 = \frac{V_0}{R_S} - \frac{V_4}{R_4'} + \frac{V_3}{R_3} - \frac{V_3}{R_3}$$

$$I_2 = \frac{V_2}{R_3} + \left(\frac{V_0}{R_S} - \frac{V_4}{R_4'} + \frac{V_3}{R_3} - \frac{V_3}{R_3}\right) = \frac{V_2}{R_2} + K_2$$

$$K_2 = \frac{V_0}{R_S} - \frac{V_4}{R_4'} + \frac{V_3}{R_3} - \frac{V_3}{R_3} + \frac{V_2}{R_3} - \frac{V_2}{R_2}$$

$$I_1 = \frac{V_1}{R_2} + \left(\frac{V_0}{R_S} - \frac{V_4}{R_4'} + \frac{V_3}{R_3} - \frac{V_3}{R_3} + \frac{V_2}{R_3} - \frac{V_2}{R_2}\right) = \frac{V_1}{R_1}$$

Resolving for R1, we get:

$$R_1 = \frac{V_1}{\frac{V_1}{R_2} + \frac{V_0}{R_S} - \frac{V_4}{R_4'} + \frac{V_3}{R_3} - \frac{V_3}{R_3} + \frac{V_2}{R_3} - \frac{V_2}{R_2}}$$

The last equation removes all K values and allows us to choose R values to try to satisfy the

desired I-V curve. Once values for R_2-R_4 were chosen, we could determine what value of R_1

would satisfy the line conditions. K values could then be determined as well as where the

voltages wanted to go as time went on to infinity. If the voltages (as time goes to infinity) of each

line go towards values determined by the switching voltages as well as the previous conditions,

then a solution would exist.

Using the MATLAB model to solve for the voltage values as t→∞, many combinations

of R values were chosen based on the conditions, trying to obtain the curve we were looking for.

Below is a table showing several of these attempts and why they failed.

Attempt	1	2	3	4	5	6	7	8
V1	3	3	3	3	3	4	1.5	5
V2	4	4	4	4	3.5	6	2	7
V3	2	2	2	2	2	3	1	4
V4	1	1	1	1	1	1	0.5	2
R1	8.72	14.24	17.11	-1.51	-3.0439	345.679	-3.1297	1000
R2	25	75	50	0.5	0.5	10	1	50
R3	500	500	1000	1500	1500	1000	1000	49
R4	5	25	75	700	700	70	700	500
Rs	50	50	50	750	750	50	500	50
$V_1 \geq$ V1	10	10	10	10	10	10	10	10
$V_2 \geq$ V2	-0.4	0.88	2.12	3.996	3.4971	4.9036	1.9953	7.375
$V_3 \leq$ V3	-0.02	-0.73	0.41	0.619	0.919	-0.2653	0.4286	7.3712
$V_4 \leq$ V4	1	1	1	1	1	1	1	10.192

Table 1. Parameter Attempts (highlights show errors)

The first three attempts shown above all had a V_2 value that was too small. Since this

value is smaller than the switching voltage, the circuit would remain stuck on this part of the

curve, never reaching V2 and thus not switching to the third curve. The V_2 value in the fourth

attempt was much closer to the switching voltage, but still not over it. The R1 value also became

negative, which is not physically possible. Still trying to see if there was a way to get an

appropriate V_2 value, we tried lowering the switching voltages. However, the V_2 value did not

get any closer to the switching voltage and the R1 value became even more negative. The sixth

attempt gave an appropriate R1 value (we want R1 to be relatively high to get the desired curve),

but again the V_2 value was too low. Figure 10 below shows the simulated outcome of the

parameter values in Attempt 6. It shows that the curve reaches the first switching voltage, but

since the second switching voltage is too low, it never reaches the second value. This causes the

circuit to just remain on the first line. In the seventh attempt, the switching voltages were all

halved, but no new results were obtained.
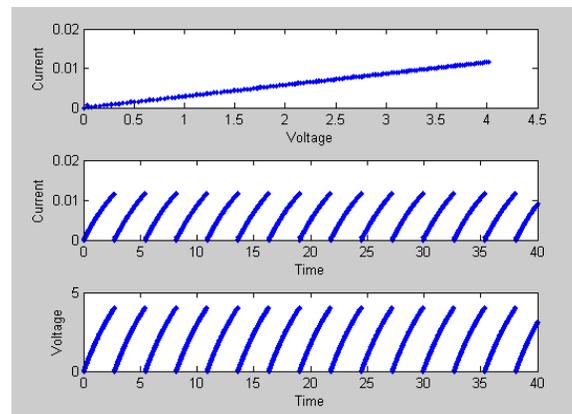
Figure 10. MATLAB model for Attempt 6

The last attempt shows just one scenario where the first and second switching voltages

are reached, but the third and fourth are not. Plugging these values into the MATLAB model to

simulate the circuit, we obtain the figures shown below. The top figure shows the circuit

switching at the first and then the second voltage. However, since the third switching voltage is

not low enough, the circuit does not complete the full path. The second figure shows the current

beginning to jump back and forth between two values as time goes on. The bottom figure shows

the voltage increasing and then leveling off.
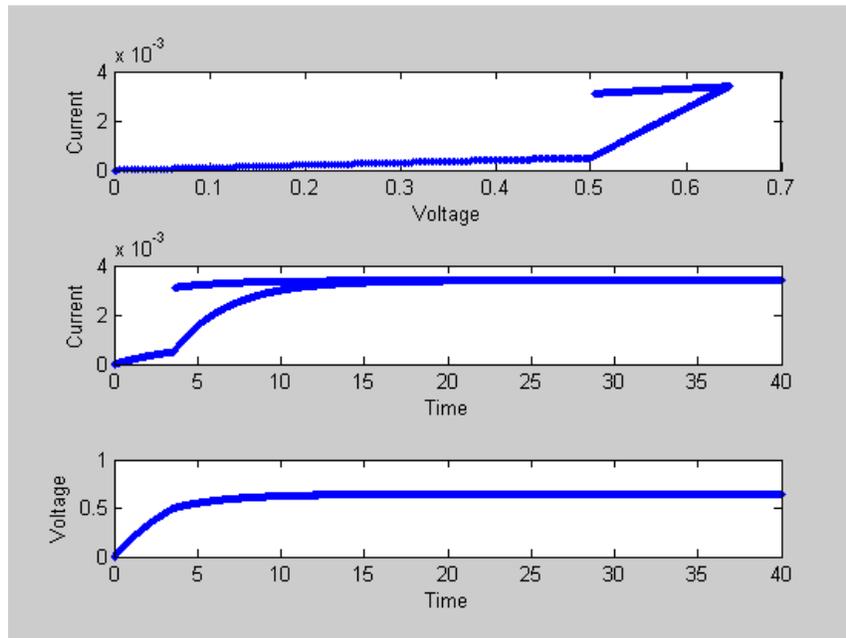
Figure 11. MATLAB model for Attempt 8

As can be seen above, for any combination of values chosen, at most only three of the voltages would reach the switching voltages. We were unable to obtain parameters that would allow for the circuit to gradually switch, as was desired. As is seen in the Simulation section, we were able to obtain a resistive switching using only two resistance values, which suggests that an instantaneous switch may be needed in order to obtain the desired results.

Chapter 5

Conclusion and Future Work

Looking into alternative ways to invert DC power to AC power in a solar cell is valuable research, as the current costs of inversion is not economical. This thesis took a look at using memristive devices in a relaxation oscillator to simulate DC to AC inversion. A model was created to test different parameters to determine if a self-oscillating system could be created that would simulate AC power taken from a DC solar cell. The simplest form of this circuit allowed the memristive device to exist at two different resistances. In this case, oscillations occurred, but only with a discontinuous current. From there, we increased the allowed number of resistances to four. This would theoretically give a continuous current as well as allow the circuit to switch at selected voltages, creating the oscillations. However, it was discovered that not all of the conditions needed for this to occur were possible. The circuit would not reach the second switching voltage, despite all other conditions satisfied. The only way the circuit would reach the second switching voltage was if several other conditions were broken.

In conclusion, while the work to obtaining a self-oscillating and continuous switching cell design is not complete, this thesis took steps in a positive direction and has developed useful ideas towards possible outlooks to a future in this area. We discovered that the circuit would not reach the second switching voltage with the current conditions, but we did not look further into allowing discontinuities in the more complex simulation with four resistances. Possibly allowing this would enable us to create a situation in which we could achieve the hysteretic curve we desire. Another possible solution is to look into different circuit designs using the memristive

elements. This could include trying to include it into an amplifying oscillating circuit. Our circuit

altered the very basic of a relaxation oscillator using only a series resistor and capacitor. By

changing the circuit, the parameters and some conditions would also change, which could lead to

more positive results. Also, since memristors are relatively new devices, there is a lot still

unknown about them and their functionality. In better understanding memristors in the future, we

may be able to construct a workable oscillating circuit using them for their resistive switching

capabilities.

Appendix A

Matlab Code for Memristive Circuit: 2 M values

```matlab
% Circuit model for memristive circuit, two M values

M1 = 10;%memristor low resistance
M2 = 100; %memristor high resistance
R = 100; %series resistance
C = 10^-3; %capacitance

delta_t = 0.0002;
t = linspace(0,20,1001);

V = zeros(1,1001);
I = zeros(1,1001);
Vs = 1;

for i=2:1000
    V(2) = 0.002;          %initializing V
    if V(i)>V(i-1)         %current voltage greater than previous voltage
        if V(i)<=0.5       %current voltage less than 0.5
            V(i+1) = ((Vs/R)+(C*V(i)/delta_t))*(R*delta_t/(delta_t+R*C));
            I(i+1) = V(i+1)/M2;
        elseif  V(i)>0.5   %current voltage greater than 0.5
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M1/(delta_t*M1+R*C*M1+R*delta_t));
            I(i+1) = V(i+1)/M1; %set next current to next voltage/Memristor
        end
    elseif V(i)<V(i-1)     %current voltage less than previous voltage
        if V(i)>=0.2       %current voltage greater than 0.2
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M1/(delta_t*M1+R*C*M1+R*delta_t));
            I(i+1)=V(i+1)/M1; %set next current to next voltage/memristor
        elseif V(i)<0.2    %current voltage less than 0.2
            V(i+1) = ((Vs/R)+(C*V(i)/delta_t))*(R*delta_t/(delta_t+R*C));
            I(i+1)=V(i+1)/M2;
        end
    end
end

subplot (3,1,1), plot(V,I,'.')
xlabel('Voltage')
ylabel('Current')

subplot (3,1,2), plot(t,I)
xlabel('Time')
ylabel('Current')
```

```
subplot (3,1,3), plot(t,V)
xlabel('Time')
ylabel('Voltage')
```

Appendix B

Matlab Code for Memristive Circuit: 4 M values

```matlab
% Circuit model for memristive circuit, four M values

% Chosen Switching Voltages
% V1 = 0.5
% V2 = 0.7
% V3 = 0.2
% V4 = 0.4

M1 = 1000;%memristive value for curve 1
M2 = 50; %memristive value for curve 2
M3 = 49; %memristive value for curve 3
M4 = 500; %memristive value for curve 4
M5 = 70;
R = 50; %series resistance
C = 10^-3; %capacitance

delta_t = 0.0002;
t = linspace(0,40,2001);

V = zeros(1,2001);
I = zeros(1,2001);

Vs = 1; %voltage from solar cell

for i=2:2000
    V(2) = 0.002;            %initializing V
    if V(i)>=V(i-1)          %current voltage greater than previous voltage
        if V(i)<=0.5         %current voltage less than 0.5
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M1/(delta_t*M1+R*C*M1+R*delta_t));
            I(i+1) = V(i+1)/M1;
        elseif 0.7>=V(i)>0.5   %current voltage greater than 0.5, less than
0.7
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M2/(delta_t*M2+R*C*M2+R*delta_t));
            I(i+1) = (V(i+1)/M2)-0.0095;
        elseif V(i)>0.7 %current voltage greater than 0.7
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M3/(delta_t*M3+R*C*M3+R*delta_t));
            I(i+1) = (V(i+1)/M3)-0.01;
        end
    elseif V(i)<V(i-1)       %current voltage less than previous voltage
        if V(i)>=0.4
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M4/(delta_t*M4+R*C*M4+R*delta_t));
            I(i+1)=V(i+1)/M4+0.0021; %set next current to next
voltage/memristor
        elseif 0.2<=V(i)<0.4    %current voltage greater than 0.1, less than
0.2
```

```
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M5/(delta_t*M5+R*C*M5+R*delta_t));
            I(i+1)=V(i+1)/M5;
        elseif V(i)<0.2
            V(i+1) =
((Vs/R)+(C*V(i)/delta_t))*(R*delta_t*M1/(delta_t*M1+R*C*M1+R*delta_t));
            I(i+1) = V(i+1)/M1;
        end
    end
end


%Plot of I-V
subplot (3,1,1), plot(V,I,'.')
xlabel('Voltage')
ylabel('Current')

%Plot of I-t
subplot (3,1,2), plot(t,I,'.')
xlabel('Time')
ylabel('Current')

%Plot of V-t
subplot (3,1,3), plot(t,V)
xlabel('Time')
ylabel('Voltage')
```

Appendix C

Matlab Code for finding voltages as t → ∞

```matlab
%Resistance values
R2 = x;
R3 = x;
R4 = x;

Rs = x;

Vo = 10;
C = 10^-3;

%chosen switching voltage
V1 = x;
V2 = x;
V3 = x;
V4 = x;

%Calculations
R_par2 = (R2*Rs)/(R2+Rs);
R_par3 = (R3*Rs)/(R3+Rs);
R_par4 = (R4*Rs)/(R4+Rs);

%Choosing our switching voltages and 3 R values, we should be able to
%calculate the value for R1 that will satisfy the curve.
R1 = V1/((-V4/R_par4)+(Vo/Rs)+(V3/R4)-(V3/R3)+(V2/R3)-(V2/R2)+(V1/R2))

R_par1 = (R1*Rs)/(R1+Rs);
%% Step 0

% find time it takes to get to V1 = V(t1)
t1 = -R_par1*C*log((-V1+Vo)/Vo)
I1 = V1/R1 %finds the current at V1

%as time goes to infinity
V_1 = Vo

%% Step 1
% Find k2 value
k2 = I1-V1/R2

t2 = t1 - (R_par2*C)*log((V2-(R_par2*((Vo/Rs)-k2)))/(V1-
(R_par2*((Vo/Rs)+k2))));
I2 = V2/R2+k2 %finds current at V2
```

```
%as time goes to infinity
V_2 = R_par2*((Vo/Rs)-k2)

%% Step 2
% find k3 value k3<=I2, but want it to be large and positive
k3 = I2 - V2/R3

t3 = t2 - (R_par3*C)*log((V3-(R_par3*Vo/Rs)+(R_par3*k3))/(V2-
(R_par3*Vo/Rs)+(R_par3*k3)));
I3 = V3/R3+k3

%as time goes to infinity
V_3 = R_par3*((Vo/Rs)-k3)

%% Step 3
% find k4 value, want k4 to be small
% need R_par4((Vo/Rs)+k4) to be less than V4

k4 = I3 - V3/R4

t4 = t3 - (R_par4*C)*log((V4-(R_par4*Vo/Rs)+(R_par4*k4))/(V3-
(R_par4*Vo/Rs)+(R_par4*k4)));
I4 = V4/R4+k4

%as time goes to infinity
V_4 = R_par4*((Vo/Rs)-k4)
```

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