The GUNNS Project

GUNNS Electrical Aspect Validation

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GUNNS Electrical Aspect Validation

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Executive Summary

The purpose of this report is to present a validation of the electrical aspect of NASA's General-Use Nodal Network Solver (GUNNS). We present hardware validation of GUNNS against physical resistor-capacitor (RC) circuit builds, and software validation against a similar COTS tool, National Instruments (NI) Multisim.

Data was collected from physical RC circuits, NI Multisim circuit models and equivalent GUNNS circuit models. The comparison of the data in this report shows that the GUNNS models performed as expected. The GUNNS model results compared very well, with some discrepancies noted. These discrepancies and their causes were examined and recommendations for improvements to the GUNNS tool set were provided. This effort validates the electrical aspect of GUNNS.

1. Introduction

1.1 Background

GUNNS is a generic software tool used for time-domain modeling of electrical, fluid, and thermal flow circuits. These circuit models, also called GUNNS ”networks”, are run in a simulation using NASA’s Trick simulation framework. The simulation and GUNNS networks that are described in this validation report used the following software tools and concepts:

- NASA’s Trick simulation framework, which provides generic capabilities and utilities for building and running time-domain simulations.
- GUNNS itself, which implements basic nodal analysis, a standard circuit analysis technique widely used in engineering.
- GunnShow, a GUI product in the GUNNS tool-set used to draw networks and generate the code and configuration files used in the Trick simulation.

GUNNS is very re-usable due to the analogous concepts that the different flow aspects share. Furthermore, it is optimized for Trick simulations, is very flexible and easy to use, and has low design and maintenance costs. These characteristics make GUNNS valuable for space vehicle simulations, particularly training and early design analysis by NASA.

Previous validation efforts have focused on the fluid and thermal aspects of GUNNS in comparison to other COTS software tools and hardware data. This report focuses on the electrical aspect of GUNNS, specifically its ability to propagate electrical circuit states and model the behavior of electrical components commonly found in spacecraft.

1.2 Comparison Tools Description

This sections describes the physical RC circuit builds and NI Multisim models that were used to compare against GUNNS.

1.2.1 Hardware Description

The hardware used for Test 1 and Test 2 was obtained from the GunnsRaCK (Resistor and Capacitor Kit), and the circuits built can be seen in Figure 1-1 and Figure 1-2 below.

For Test 1, the circuit is a simple charging/discharging RC circuit. When the switch is ON (closed), the capacitor is charging. When the switch is OFF (open), the capacitor is discharging. The capacitor voltage is measured using a Saleae Logic 8 Analyzer, also shown. The logic analyzer’s leads are connected to the breadboard’s ground channel and the input terminal of the capacitor (C1), so it measures the voltage across the capacitor referenced to ground. A diagram of this circuit is shown in Figure 1-8.

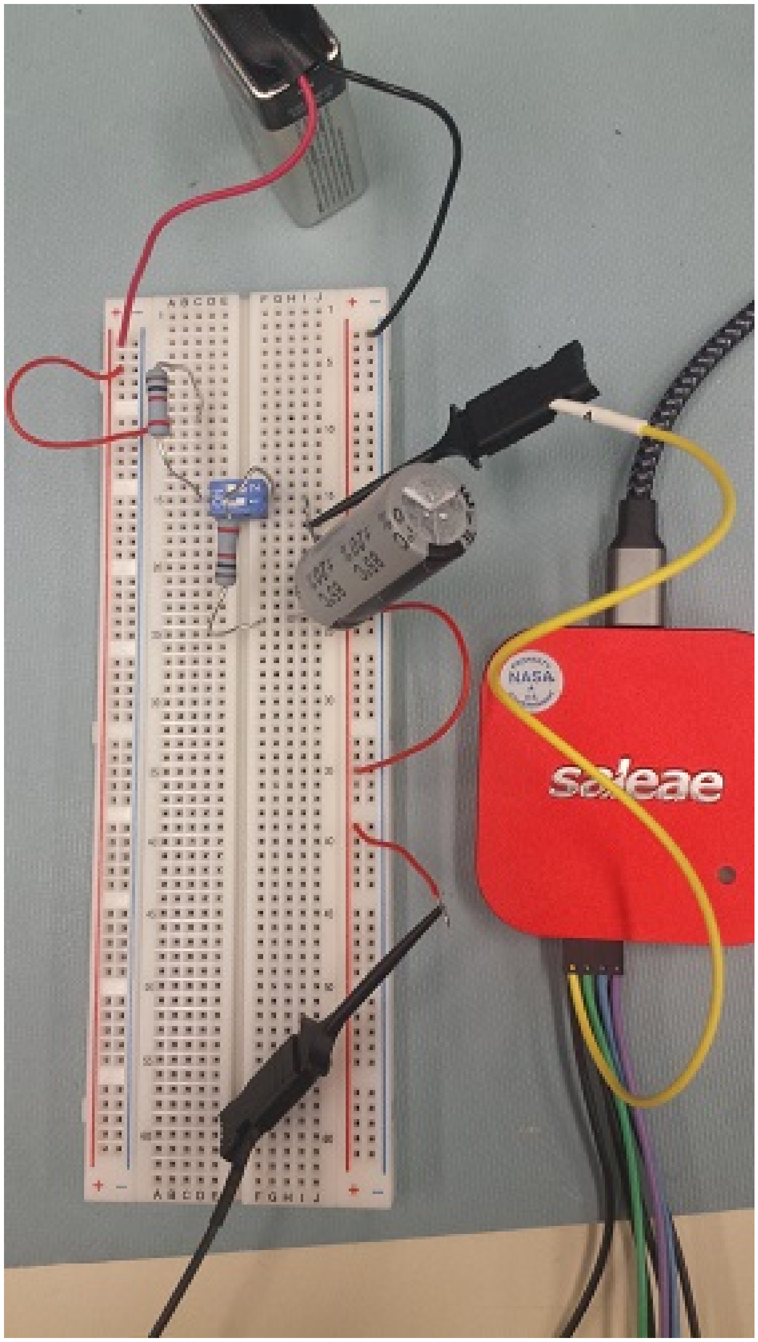


Figure 1-1: Hardware RC Network 1.

For Test 2, the circuit design is more complicated. It is used to test the GUNNS ability to solve more complex circuits. The logic analyzer measures the voltage across the lower capacitor (C2) referenced to ground. A diagram of this circuit is shown in Figure 1-9.

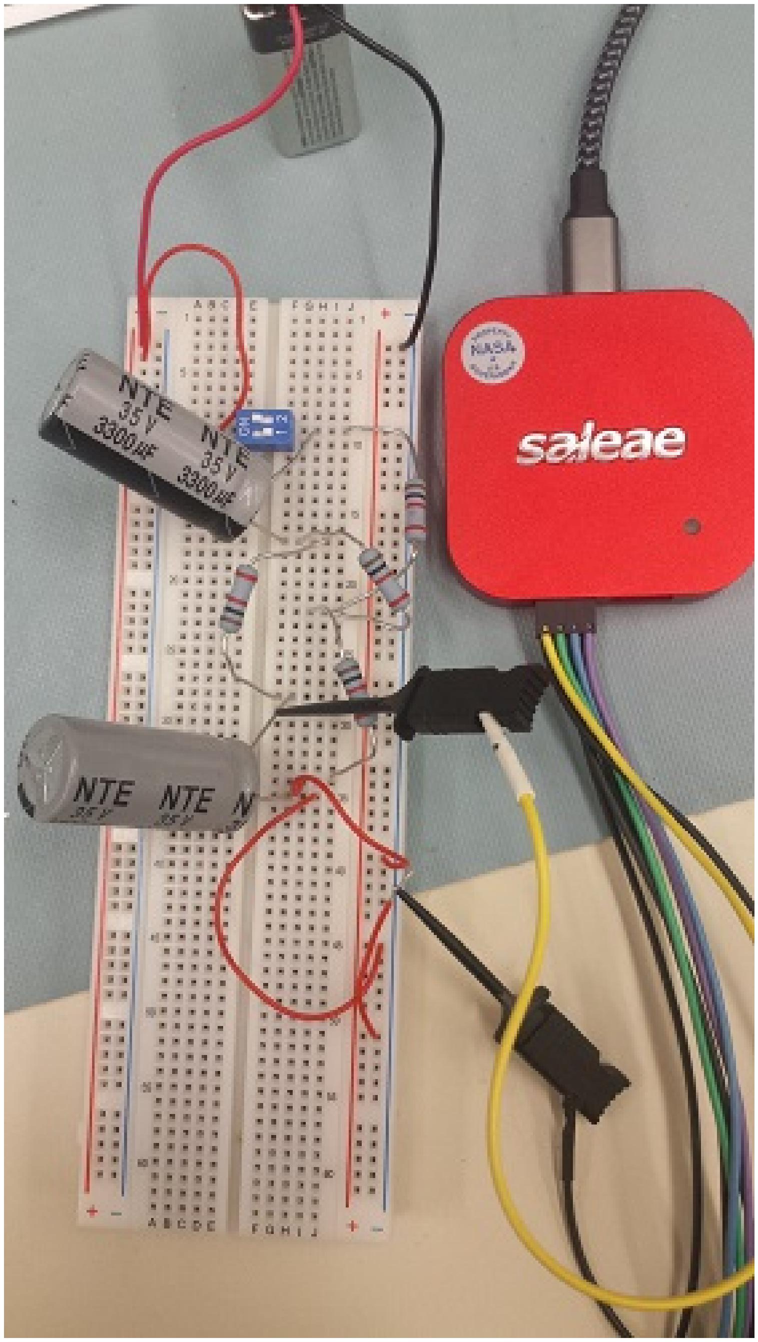


Figure 1-2: Hardware RC Network 2.

1.2.2 Software Description

For Tests 3 through 7, NI Multisim was used to compare to the model outputs. NI Multisim is an industry-standard circuit simulation software used worldwide by engineers and scientists. Due to its wide range of use, we can be confident in its accuracy and that it is a good benchmark for validating GUNNS against.

For these tests, the NI Multisim circuit was propagated inside Multisim. Various voltage and current output values around the circuit were logged for comparison with GUNNS.

For Test 3, a complicated RC circuit with current sources was made and can be seen in Figure 1-3. This circuit is complex enough to be too impractical to solve by hand using Ohm's and Kirchhoff's Laws, thus necessitating solver tools such as GUNNS and NI Multisim. It has two identical sub-circuits, each powered by its own current source. Since these sub-circuits are identical, we expect their solutions to be identical.

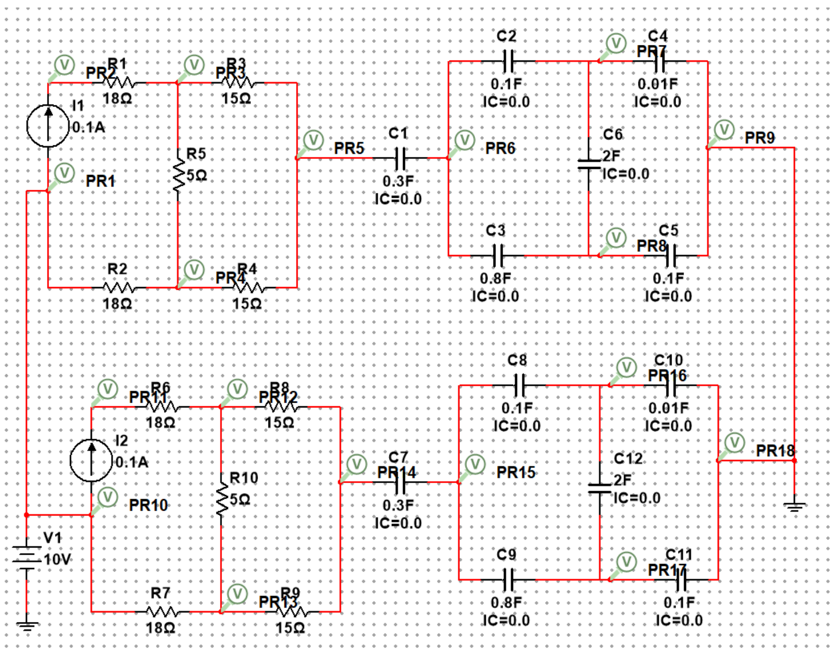


Figure 1-3: NI Multisim Complicated RC Network.

Figure 1-4 shows the NI Multisim model used in Test 4. This contains, shown from top to bottom, real diode, ideal diode, and real diode equivalent circuits, each powered by a voltage source and charging a capacitor. The real diode equivalent circuit is used to show that a real diode can be modeled by combining an ideal diode in series with an opposing voltage source.

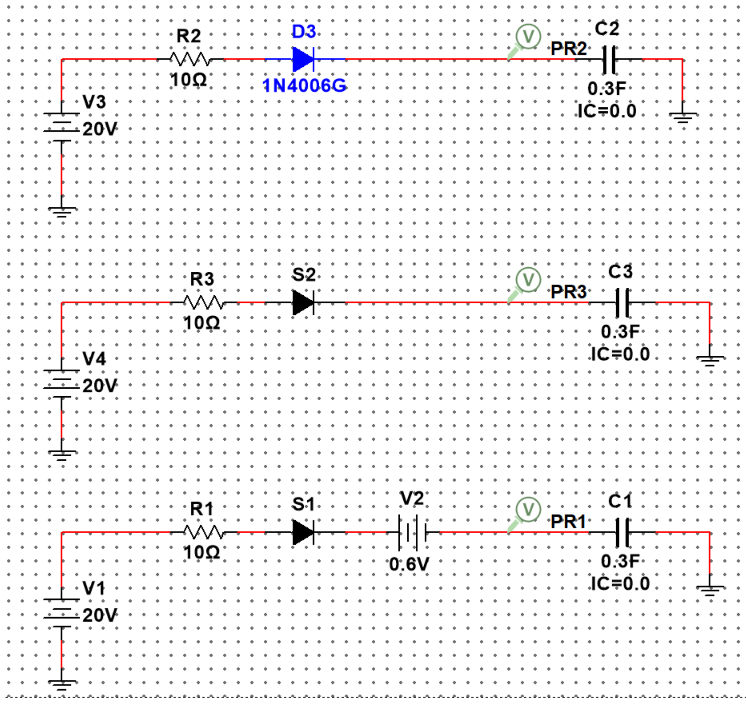


Figure 1-4: Diode Networks.

Test 5 contains two functionally equivalent circuits, shown in Figure 1-5. Each models a solar cell powering a capacitor in parallel with a resistive load. This load configuration is greatly simplified, but functionally similar to, typical space vehicle power load configurations. The top circuit uses an integrated solar array model in NI Multisim. The lower circuit models the solar array as an equivalent circuit of components, but is otherwise identical to the upper circuit. These two circuits are used to contrast the performance of integrated vs. equivalent solar array models.

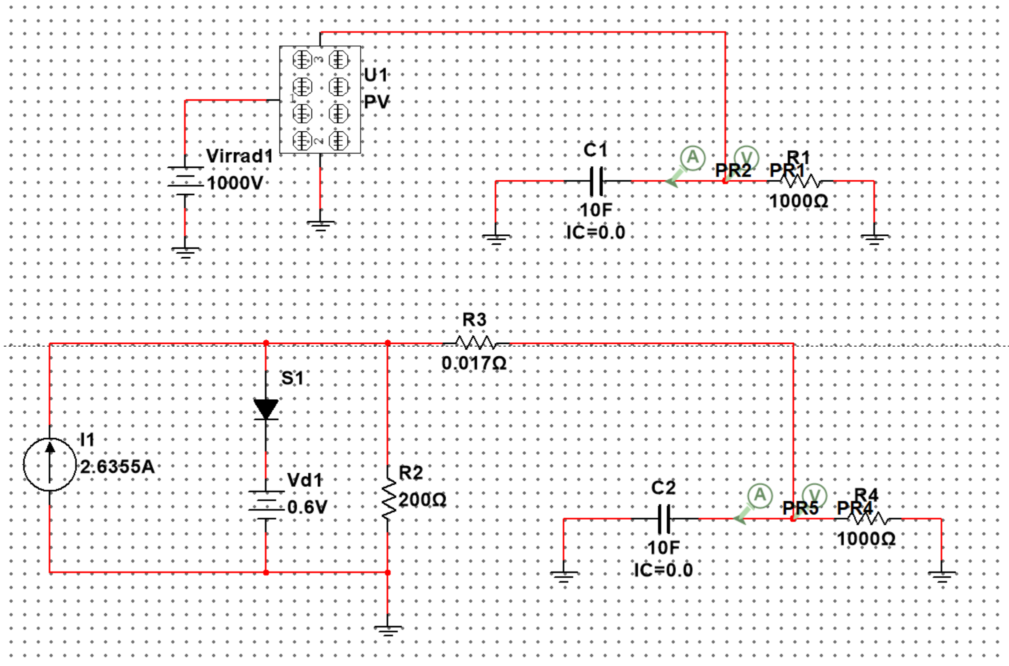


Figure 1-5: NI Multisim Single Cell Solar Array Network.

For Test 6, the single solar array cell and its equivalent circuit were both scaled up to become a multiple cell solar array and equivalent circuit, as seen in Figure 1-6. The rest of the circuit is unchanged from Test 5.

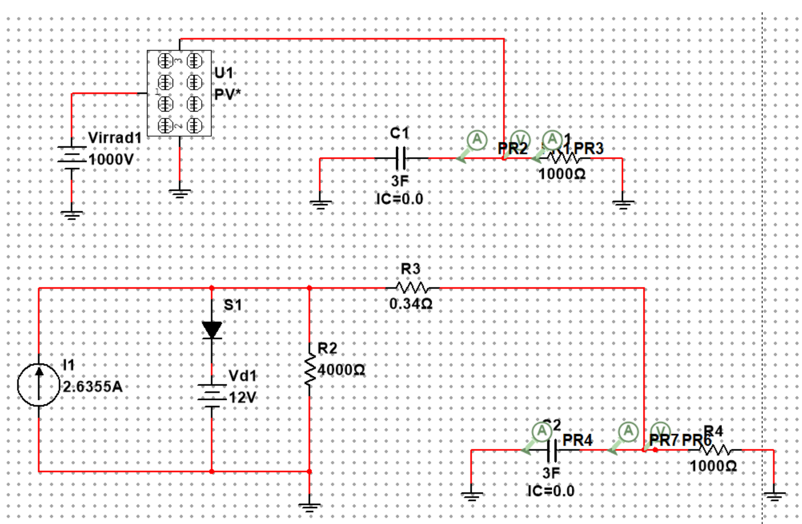


Figure 1-6: NI Multisim Multiple Cell Solar Array Network.

For Test 7, a voltage regulator network was built as seen in Figure 1-7. The regulator's purpose is to take any input voltage and regulate it to a chosen output voltage. The output voltages and currents in the circuit were observed.

The circuit layout in Test 7 resembles the electrical power supply and distribution system typically found in modern crewed spacecraft. That is, multiple strings of distribution systems powered by solar arrays, with a controller to regulate the voltage supplied to the vehicle systems. This type of system is the most typical use of the GUNNS electrical aspect, so it is important to validate its performance here.

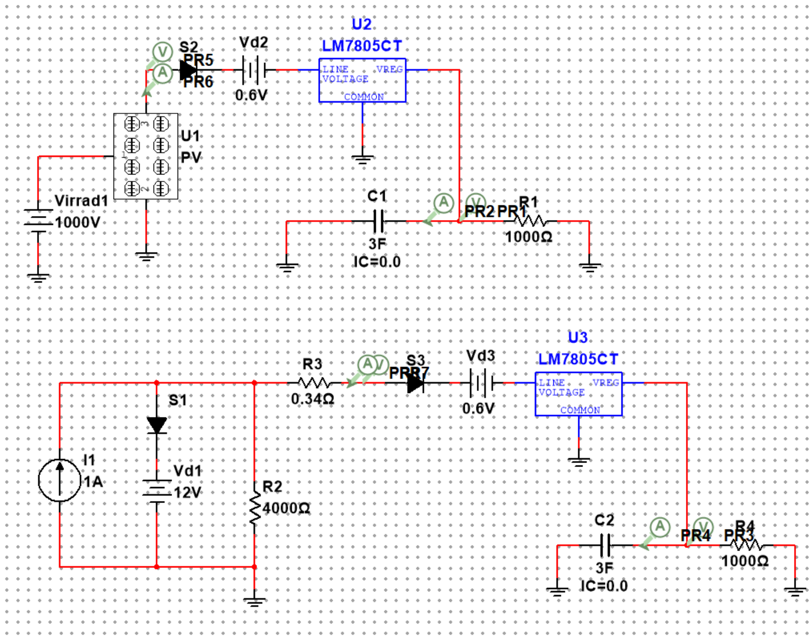


Figure 1-7: NI Multisim Voltage Regulator Network.

1.3 Model Description

For each test, the GUNNS model consists of two major components:

- A GUNNS electrical network modeling the electrical circuit. The circuit layout for each test is shown in the figures below.
- The Trick input file, used to set up initial test conditions and data logging.

Figure 1-8 shows the GUNNS model used to compare against the simple RC physical circuit in Test 1.

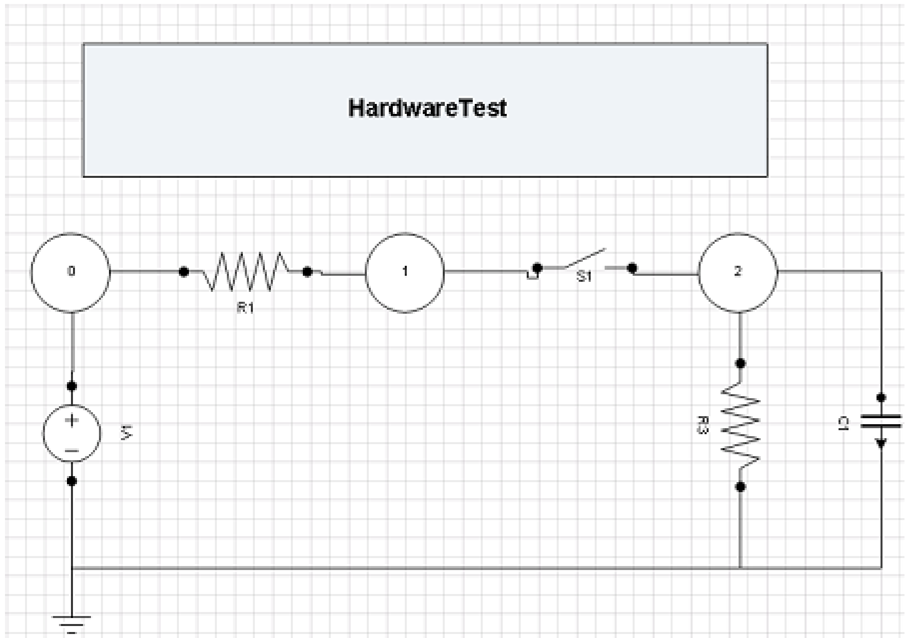


Figure 1-8: GUNNS Hardware Network 1.

Figure 1-9 shows the GUNNS model used to compare against the complex RC physical circuit in Test 2.

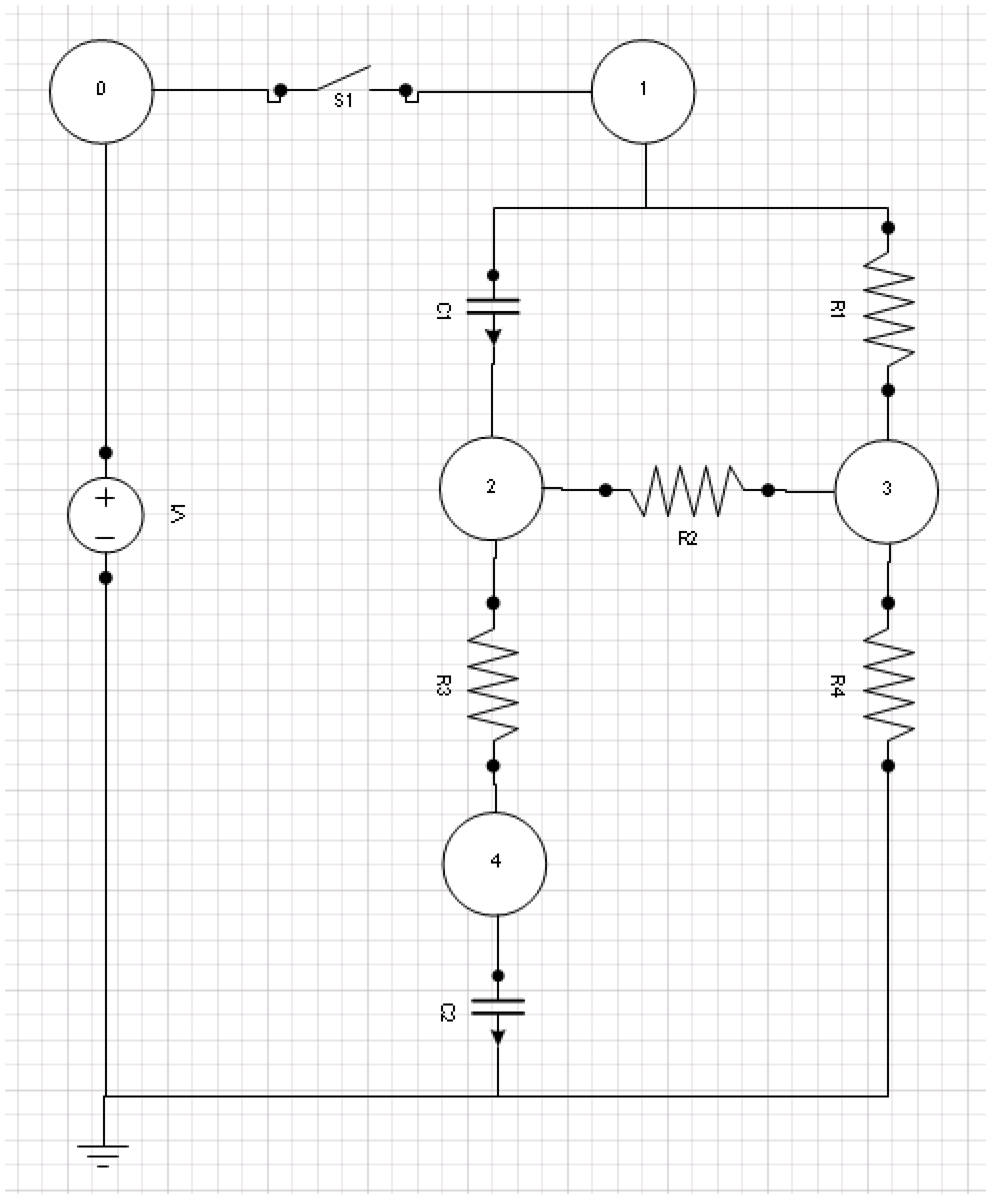


Figure 1-9: GUNNS Hardware Network 2.

Figure 1-10 shows the GUNNS model used to compare against the complex RC NI Multisim circuit in Test 3.

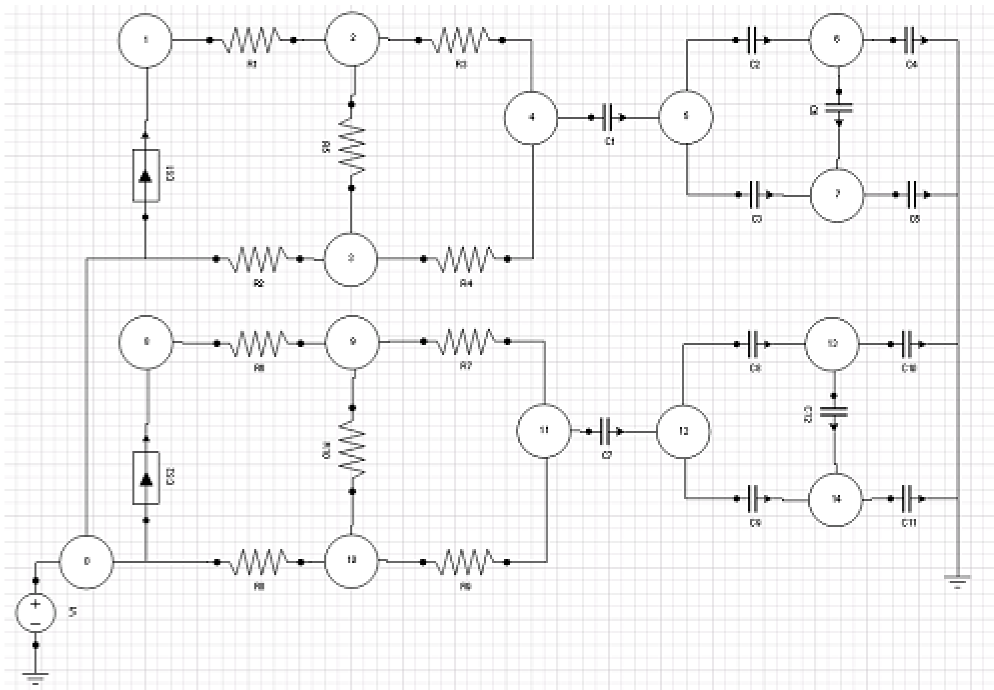


Figure 1-10: GUNNS Complicated RC Network.

Figure 1-11 shows the GUNNS model used to compare against the single solar cell NI Multisim circuit in Test 5. Like the NI Multisim network, the lower sub-circuit uses individual components to make an equivalent circuit of the solar cell. However in this GUNNS network, we model the real diode by combining an ideal GUNNS diode in series with an opposing voltage source, as shown in Test 4.

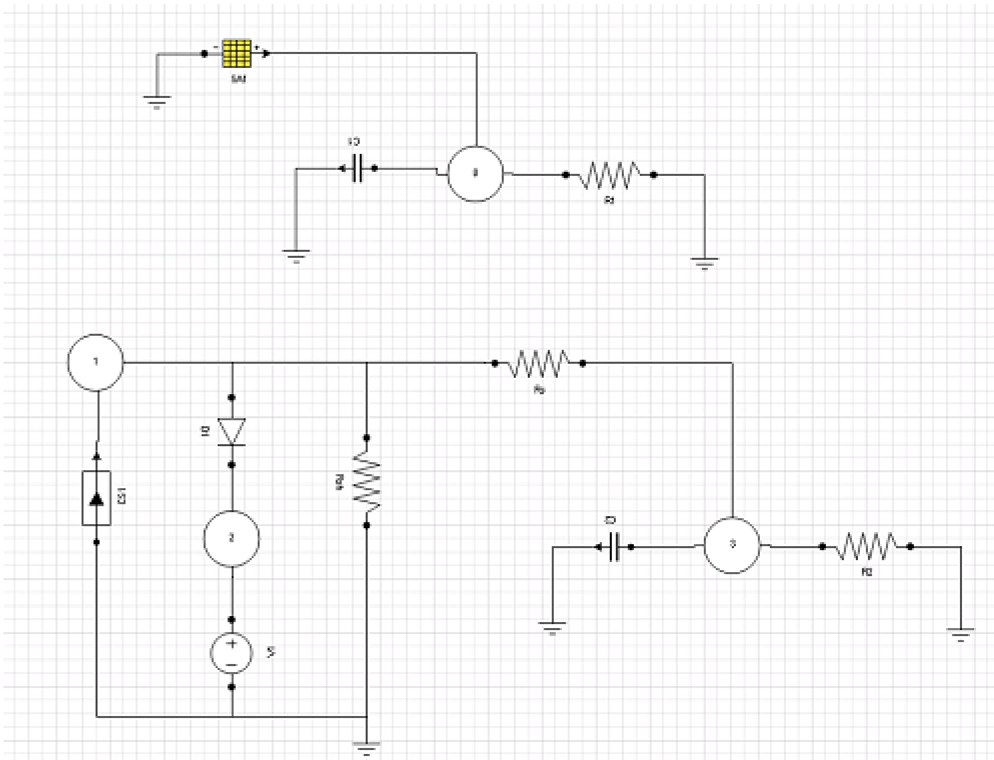


Figure 1-11: GUNNS Single Cell Solar Array Network.

Figure 1-11 shows the GUNNS model used to compare against the multi-cell solar array NI Multisim circuit in Test 6. This GUNNS network is identical to the Test 5 network, except the solar array link and equivalent components are scaled up to model multiple cells.

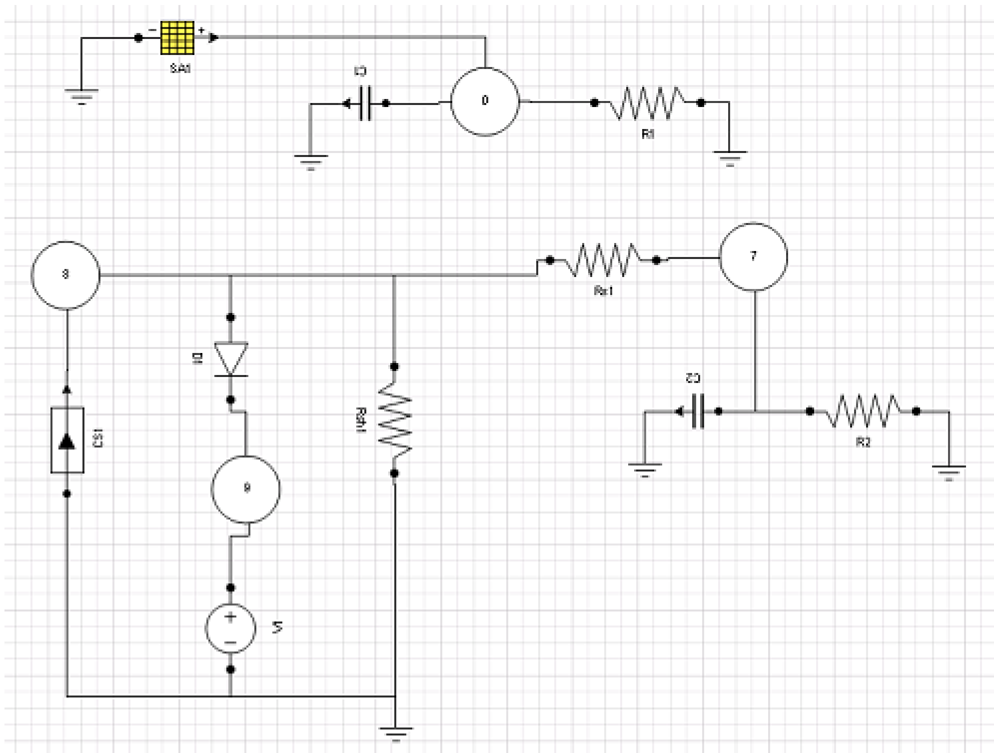


Figure 1-12: GUNNS Multiple Cell Solar Array Network.

Figure 1-11 shows the GUNNS model used to compare against the voltage regulator NI Multisim circuit in Test 7. Like Tests 5 and 6, we model real diodes by adding an opposing voltage source to each ideal diode. This GUNNS network differs from the NI Multisim network in a few important ways:

- NI Multisim has no equivalent to the GUNNS Solar Array Regulator (SAR) model, so we used the closest thing NI Multisim had available, which is a voltage regulator. These models differ in a few important ways, which affects the comparison and is discussed below.
- This GUNNS circuit contains a battery in parallel with the solar array, which is typical of actual spacecraft power system designs. The battery switch was left open so the battery does not contribute to this test.

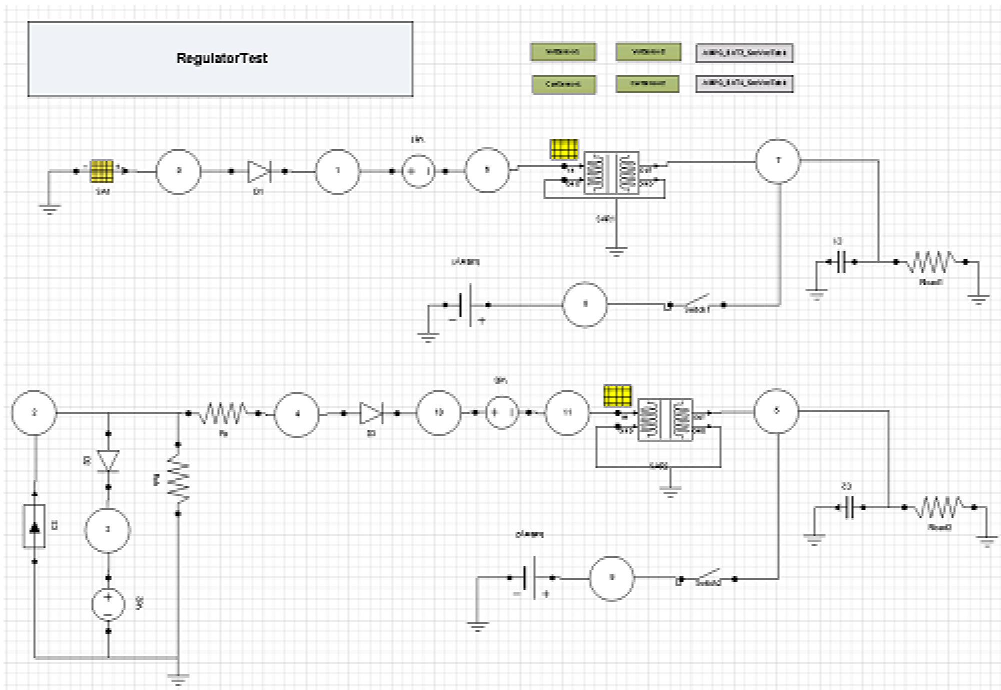


Figure 1-13: GUNNS Voltage Regulator Network.

1.4 Model Scope, Limitations and Assumptions

1.4.1 Model Scope

The following GUNNS links were verified throughout the tests in this report:

- Resistor
- Capacitor
- Battery
- Solar Array
- Solar Array Regulator
- Switch
- Voltage Source
- Current Source
- Diode

The following GUNNS links were not verified in this report because they are less commonly used than those listed above:

- Constant Power Load
- Constant Current Load
- Electric Converter

- Jumper
- Power Function Resistor
- Resistive Load
- Selector Switch
- Socket
- Switch Card
- User Loads

1.4.2 Limitations

The GUNNS Battery and SAR links were only be partially verified.

For the Battery, we validated its ability to act like a voltage source, but we did not validate its voltage drop from internal resistance or the effects of the battery discharging. A real battery voltage decreases as a function of percent of capacity discharged, discharge rate, temperature, and material. Over time, a battery's internal resistance increases, which causes the battery's output to decrease under the same current. These effects are not fully modeled in the GUNNS battery model. Further work should be done in the future for more comprehensive validation of the battery link.

For the SAR, there is not a similar enough model in NI Multisim. The closest model in NI Multisim is a voltage regulator. These models differ in several important ways:

- When the SAR regulates output voltage, it can both down-convert a higher input voltage and up-convert a lower input voltage to the regulated output voltage. Thus the output voltage is regulated regardless of input voltage. The NI Multisim regulator does not up-convert a lower input voltage, so its output voltage cannot be maintained higher than the input. The effect of this difference in our tests is that during conditions when the input voltage is less than the regulator set-point, the GUNNS and NI Multisim output voltages differ.
- On the input side, the NI Multisim regulator limits the input current to a maximum value, whereas the GUNNS SAR link does not. In our tests, the GUNNS SAR can create much higher input-side currents than the limited input current in the NI Multisim regulator.
- The GUNNS SAR and NI Multisim voltage regulator model two different physical technologies. The NI Multisim regulator models a simple voltage dropper resistor, which dissipates the excess voltage from higher input voltage to the regulated output voltage as waste heat. In contrast, the GUNNS SAR models a solid-state switching conversion circuit.
- As a result of modeling the different internal technology, the GUNNS SAR conserves power from input to output, whereas the NI Multisim regulator conserves current.
- The GUNNS SAR also regulates a portion of its output current to charge a downstream battery, by actively controlling its output voltage to maintain a desired charge current measured at the battery. The NI Multisim regulator has no such function. This difference is not significant for our tests however, since we isolate the battery from the GUNNS SAR and turn its battery charging mode off.

GUNNS contains an ideal diode model but lacks a real diode model. We worked around this limitation in the GUNNS networks by adding a series voltage source opposing the diode, as described above.

1.4.3 Assumptions

The GUNNS model runs at 10 Hz. A higher frequency model would be more accurate, but the accuracy gained from increasing the frequency is not worth the extra computing power required. In comparison, Multisim uses dynamic time steps, depending on the behavior of the curve that is being modeled. If the curve is changing rapidly, then smaller time steps are used, and vice-versa. We assume that these different integration schemes produce negligible differences in circuit output.

1.5 Validation Objectives

This report aims to:

- validate the nodal analysis circuit solver at the heart of GUNNS,
- validate the main GUNNS effects (potential source, flow source, capacitance and conductance),
- verify that the typical execution frequency of GUNNS networks provides sufficient accuracy,
- validate the GUNNS models of the most commonly electrical circuit components,
- verify that GUNNS can accurately predict real hardware circuit performance, and
- verify that GUNNS solutions agree with reputable COTS software used in industry.

2. Test Methodology

This section details the GUNNS and NI Multisim simulation setup for the seven tests that were performed.

2.1 Model Tuning

Typically, GUNNS networks are ”tuned” to produce the best accuracy. In the electrical aspect, this means using the actual measured parameter of an electrical component instead of its rated value. For instance, a resistor with a certain rated resistance may have a different actual resistance, and using its actual resistance in the circuit model produces better agreement with its real-world performance.

For Tests 1 and 2, we tuned the model to match the measured hardware values. The exact parameters of the hardware resistor and battery components were measured with a Extech DM110 Pocket MultiMeter for full accuracy. We found that for Test 1, the resistors had an actual resistance of 993 ohms, and the battery supplied 9.4 volts. For Test 2, the resistors had an actual resistance of 993, 991, 993 and 996 ohms respectively, and the battery supplied 9.4 volts.

For Tests 3 through 7, since we are comparing software to software, we can use the same ideal component values in each application with no tuning needed.

2.2 Model Initial Conditions

For Tests 1-7, the component values are given in the tables below. The component numbers correspond to the GUNNS networks shown in Section 1.4. For components that have many inputs, such as the solar array regulator, only values that were changed from the default values are given. The actual capacitance of the capacitors could not be measured by our multimeter, so we assumed that the rated and actual values were the same. Because the internal resistance of the battery would be negligible in comparison to the resistance of the other components in the networks, the internal resistance was not considered significant and was omitted.

Component	**Value**
Rated R1 and R2	1000 ohms
Rated C1	3300 uF
Rated V1	9 V
Actual R1 and R2	993 ohms
Actual C1	3300 uF
Actual V1	9.4 V

Table 2-1: Test 1 Rated and Actual Component Values

Component	Value
Rated R1, R2, R3, and R4	1000 ohms
Rated C1 and C2	3300 uF
Rated V1	9 V
Actual R1 and R3	993 ohms
Actual R2	991 ohms
Actual R4	996 ohms
Actual C1 and C2	3300 uF
Actual V1	9.4 V

Table 2-2: Test 2 Rated and Actual Component Values

Component	Value
R1, R2, R6, R7	18 ohms
R3, R4, R8, R9	15 ohms
R5, R10	5 ohms
C1, C7	0.3 F
C2, C5, C8, C11	0.1 F
C3, C9	0.8 F
C4, C10	0.01 F
C6, C12	2 F
V1	10 V

Table 2-3: Test 3 Component Values

Component	Value
R1, R2, R3	10 ohms
V1, V2, V3	20 V
C1, C2, C3	0.3 F
V4	0.6 V

Table 2-4: Test 4 Component Values

Component	Value
R1, R2	1000 ohms
C1, C2	3 F
Isc, CS1	2.6355 amps
Rsh	200 ohms
Rs	0.017 ohms
V1	0.6 V
numSections	1
numStrings	1
numCells	1

Table 2-5: Test 5 Component Values

Component	**Value**
R1, R2	1000 ohms
C1, C2	3 F
Isc, CS1	2.6355 amps
Rsh	4000 ohms
Rs	0.34 ohms
V1	12 V
numSections	1
numStrings	1
numCells	20

Table 2-6: Test 6 Component Values

Component	**Value**
Rload1, Rload2	1000 ohms
C1, C2	3 F
Isc, CS1	1 amp
Rsh	4000 ohms
Rs	0.34 ohms
Vd2	12 V
Vd1, Vd3	0.6 V
SA1, SA2 numSections	1
SA1, SA2 numStrings	1
SA1, SA2 numCells	20
SAR1, SAR2 standbyPower	0 W
SAR1, SAR2 regulatedVoltageLowLimit	5 V
SAR1, SAR2 regulatedVoltageHighLimit	7 V
SAR1, SAR2 regulatedVoltage	6 V
SAR1, SAR2 efficiency	1
SAR1, SAR2 proportionalGain	1e-15
SAR1, SAR2 derivativeGain	1e-15

Table 2-7: Test 7 Component Values

2.3 Model Data Collection

Trick's Data Recording Editor was used to acquire GUNNS model data for comparison with the hardware and NI Multisim data in Tests 1-7. The following GUNNS model terms and their units were logged at 0.1 second intervals:

Test 1:

- Capacitor 1 Voltage

Test 2:

- Capacitor 2 Voltage

Test 3:

- Capacitors 1-12 Voltages
- Capacitors 1-12 Currents

- Resistors 1-10 Voltages
- Resistors 1-10 Currents

Test 4:

- Capacitors 1-3 Voltages

Test 5:

- Node 0 Voltage
- Resistor 1 Current
- Node 3 Voltage
- Resistor 2 Current

Test 6:

- Node 0 Voltage
- Resistor 1 Current
- Node 7 Voltage
- Resistor 2 Current

Test 7:

- Capacitor 1 Voltage
- Capacitor 1 Current
- Capacitor 2 Voltage
- Capacitor 2 Current
- Solar Array Regulator 1 Power
- Solar Array Regulator 2 Power

During comparison of this logged GUNNS data with the physical circuit's logic analyzer data and the NI Multisim data, it became apparent that there was a 0.1 second discrepancy in the time tag of the GUNNS data. This turned out to be a known Trick limitation, and is discussed below. In the interest of making the best possible comparison, we corrected the time tag in the logged GUNNS data.

3. Test Observations

This section presents comparisons of the GUNNS model to software and hardware results. Discrepancies in the data are discussed in Section 4. Many comparisons were redundant, and only the most relevant are shown here. The remainder are included in the Appendix.

3.1 Test 1

We present a comparison of the model's performance against hardware and software for a simple RC network which undergoes charging and discharging. Due to the limits of the Saleae logic analyzer, only the voltage data could be obtained from the hardware.

3.1.1 Charging

Figures 3-1 and 3-2 compare the output voltage of the GUNNS model to two runs of the hardware when charging the circuit. We observe that both test runs of the hardware match the GUNNS model extremely well. There is a small discrepancy in voltage while the capacitor is charging, but it converges as the capacitor charging completes.

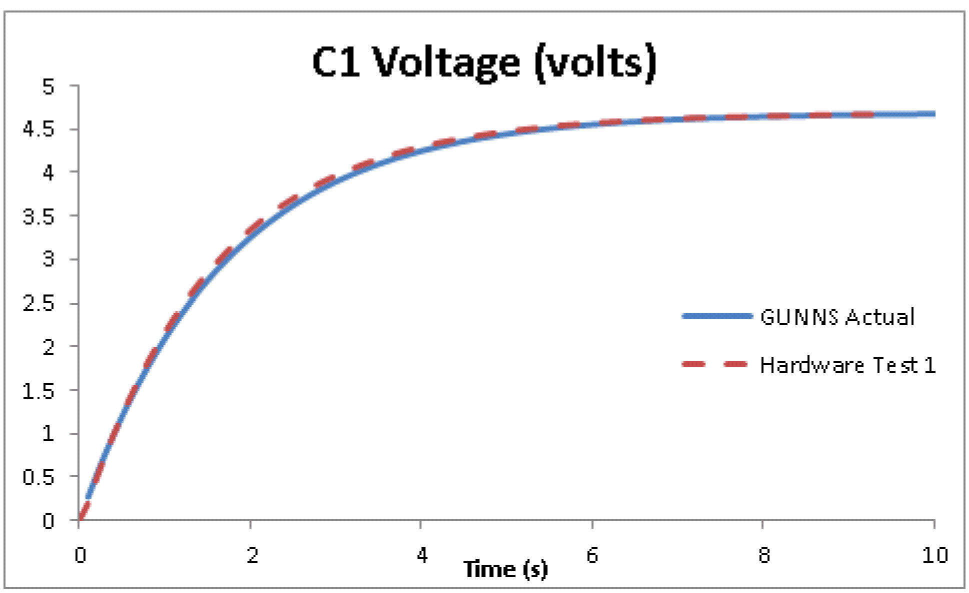


Figure 3-1: Run 1 C1 Voltage.

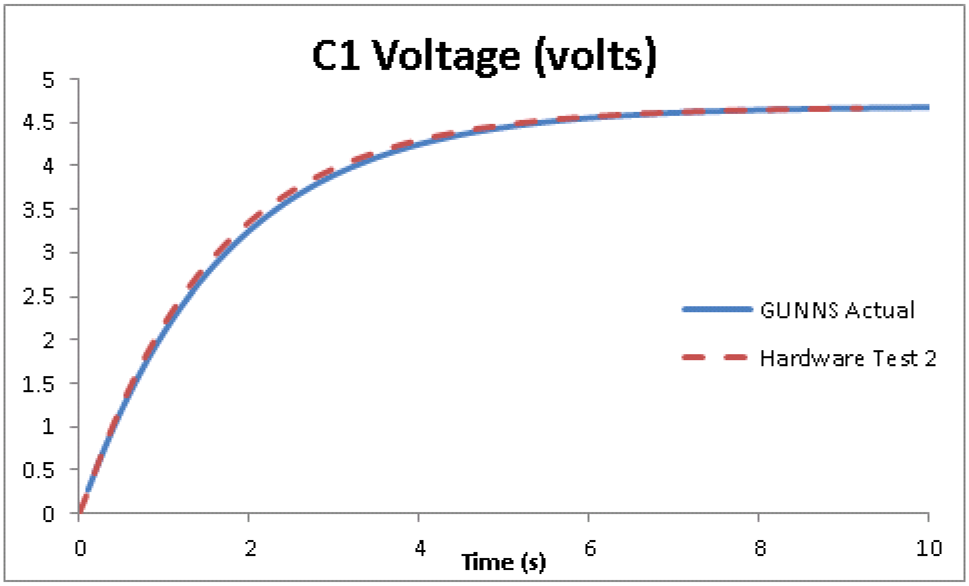


Figure 3-2: Run 2 C1 Voltage.

Figure 3-3 demonstrates the difference in GUNNS model output between using the rated and actual hardware values. We observe that using the actual, measured values of the components rather than the rated values makes a large improvement in the accuracy of the model. This shows the importance of tuning GUNNS networks to actual hardware values.

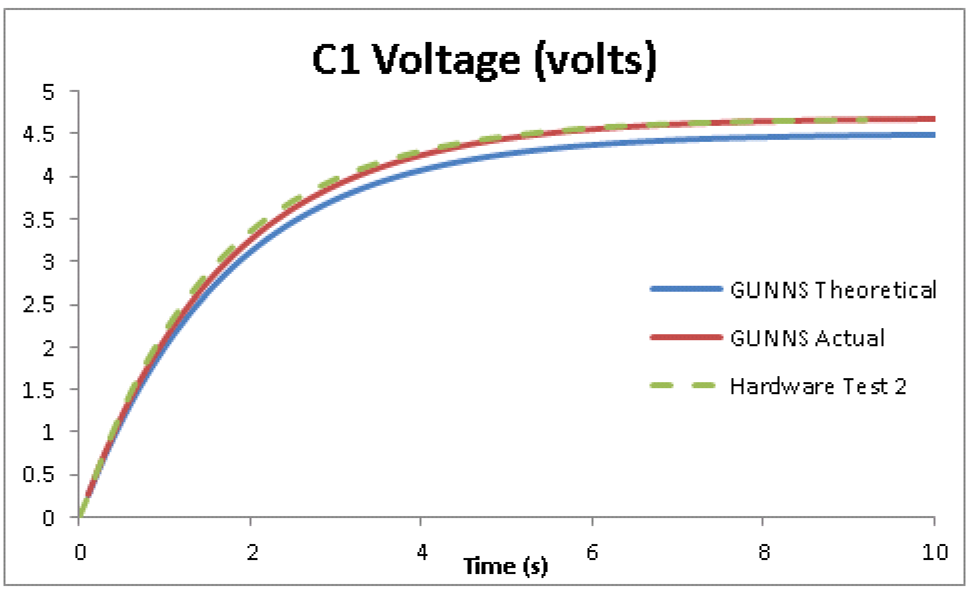


Figure 3-3: Theoretical vs Actual C1 Voltage.

3.1.2 Discharging

Figures 3-4 and 3-5 compare the output voltage of the GUNNS model to two runs of the hardware when discharging the circuit. We see similar results as in the charging case.

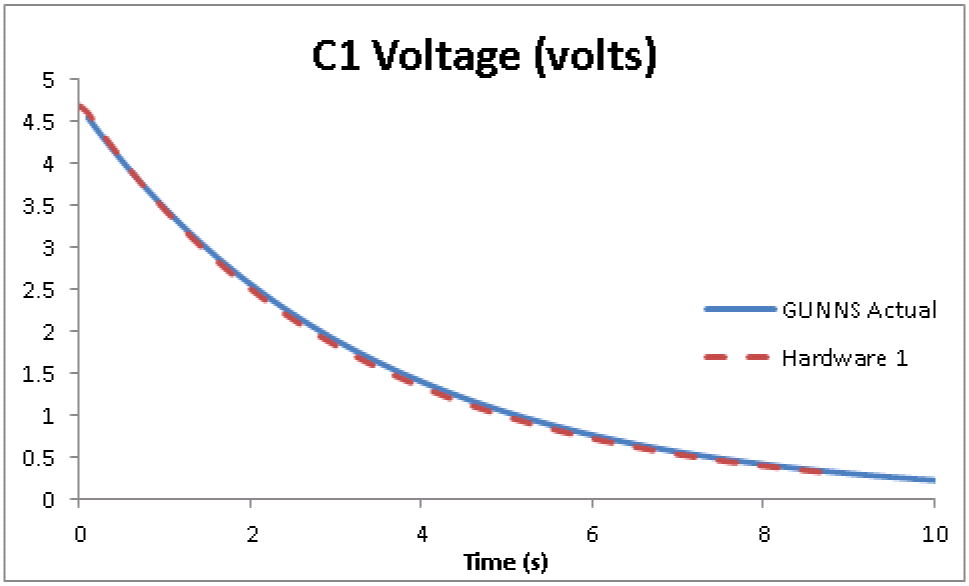


Figure 3-4: Run 1 C1 Voltage.

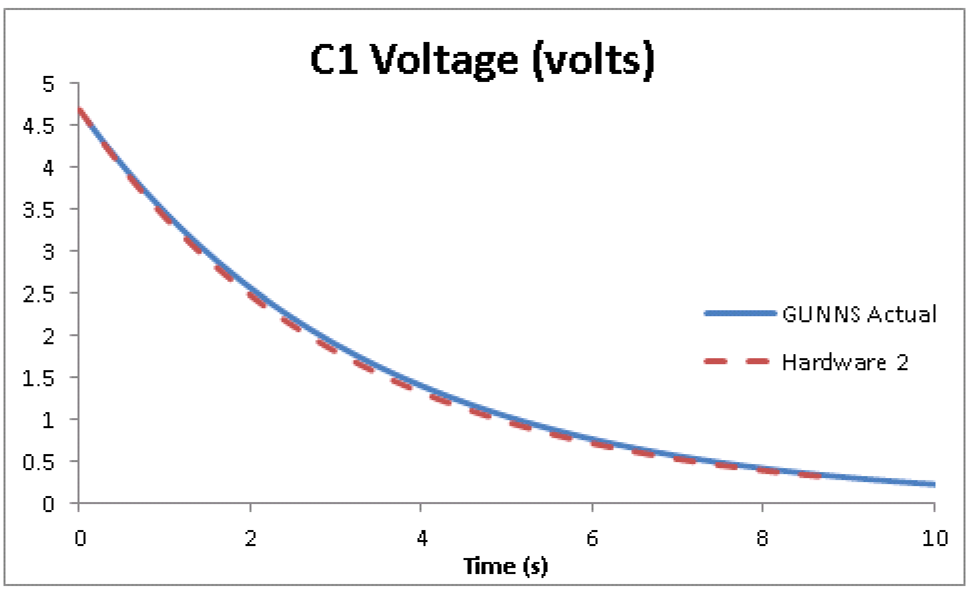


Figure 3-5: Run 2 C1 Voltage.

Figure 3-6 demonstrates the difference in GUNNS model output between using the rated and actual hardware values. We observe much less of a difference than in the charging case. This is because when the circuit is discharging, the battery and one of the resistors have been disconnected from the network, so there is now only one component (the discharge resistor) contributing a difference.

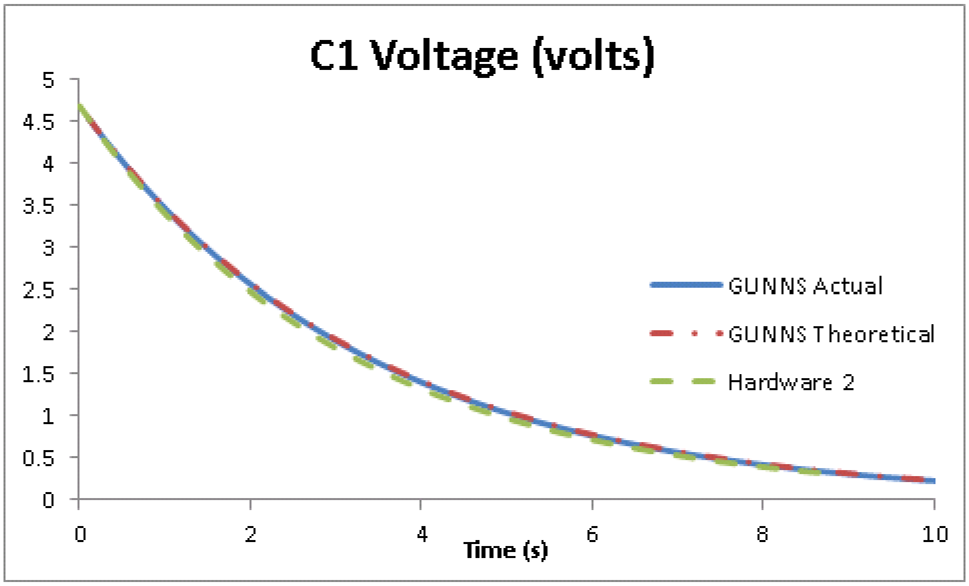


Figure 3-6: Theoretical vs Actual C1 Voltage.

3.2 Test 2

We present a comparison of the model's performance against hardware for a more complex RC network. Similar to Test 1, only the voltage data from this test could be obtained. Additionally, the Saleae Logic 8's maximum analog voltage rating is 5 volts, so only Capacitor 2's voltage could be measured.

Figure 3-7 compares the output voltage of the model to that of the hardware.

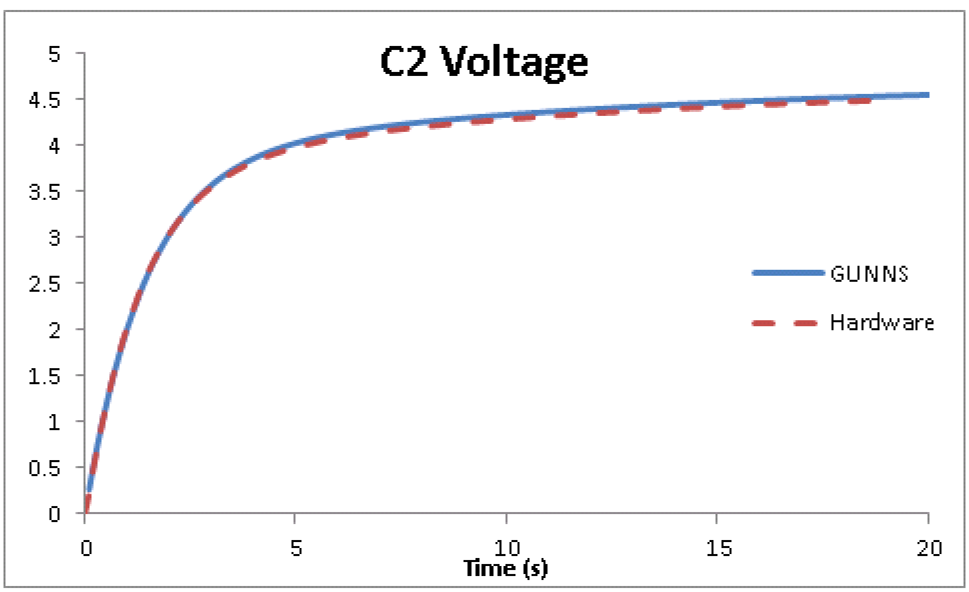


Figure 3-7: C2 Voltage.

3.3 Test 3

We present a comparison of the model's performance against software for a very complex RC network which undergoes charging.

The figures below compare the output voltage and current of the GUNNS model to that of the NI Multisim model.

From the schematic of the RC network from Section 1.3, we can see that the upper and lower halves of the network are both in parallel and identical. This means that the voltage and current going to each component should mirror each other in the upper and lower half of the network. From our results, we can see that this is true. The corresponding capacitors, nodes, and resistors in each half of the circuit exhibited the exact same behaviors. Finally, we observe that the GUNNS and NI Multisim models compare very well.

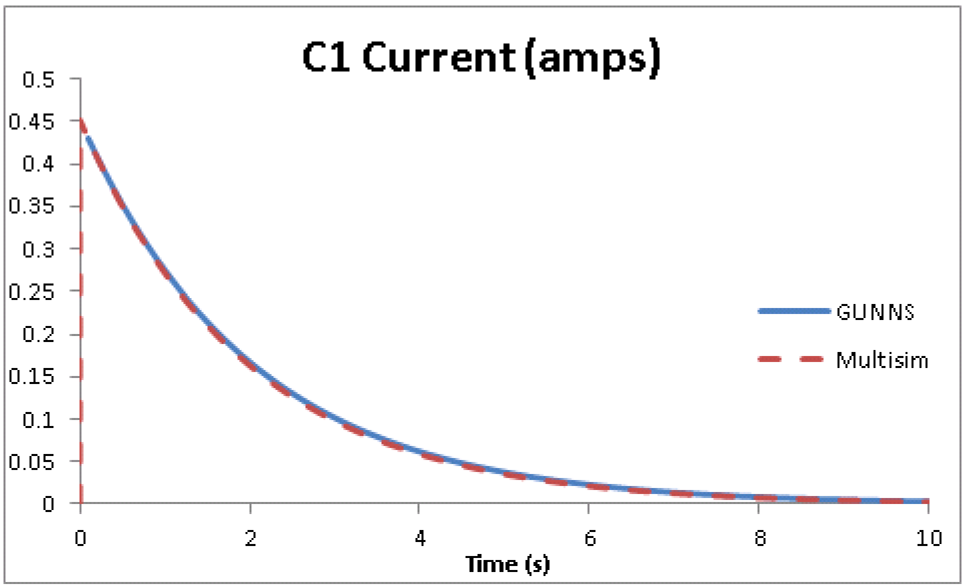


Figure 3-8: C1 Current.

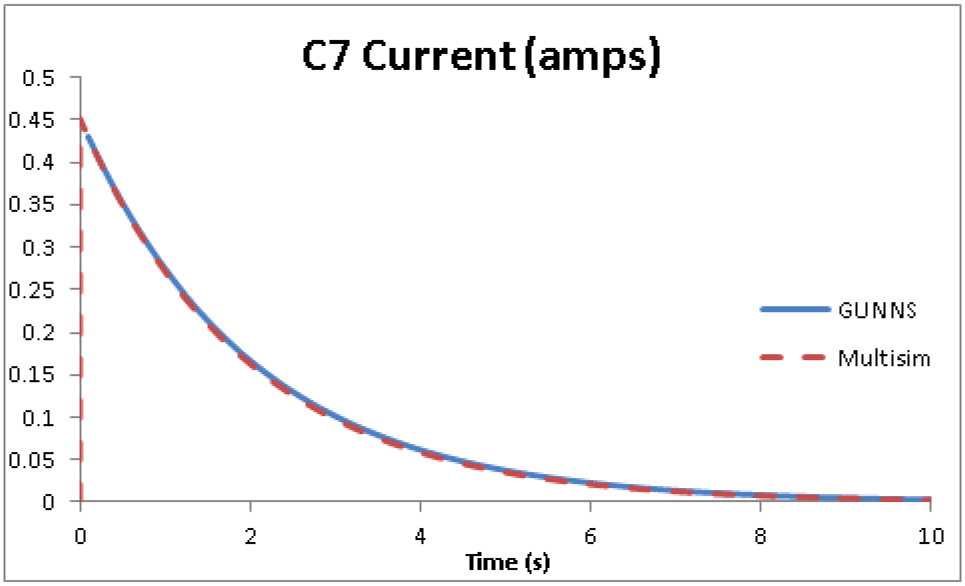


Figure 3-9: C7 Current.

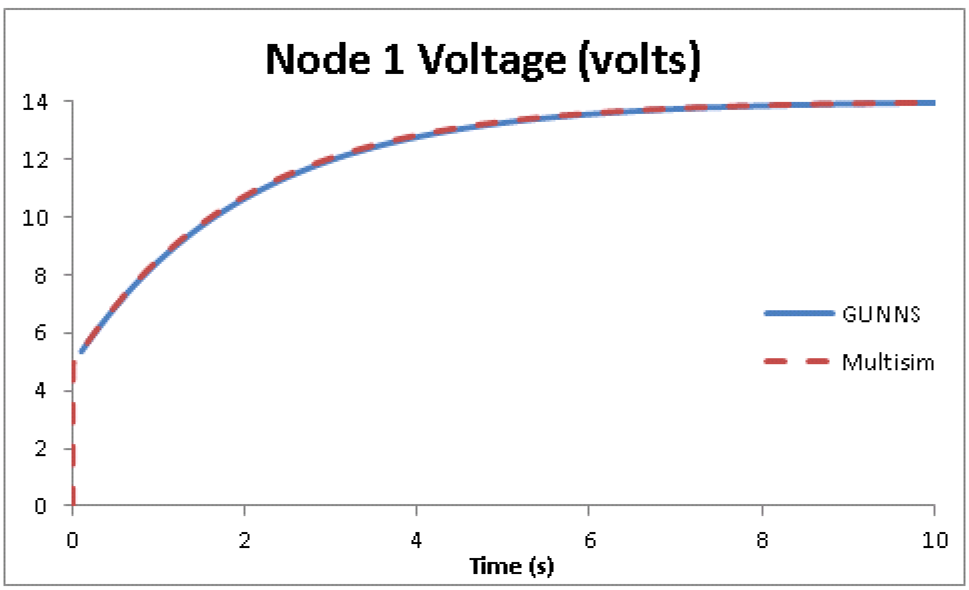


Figure 3-10: Node 1 Voltage.

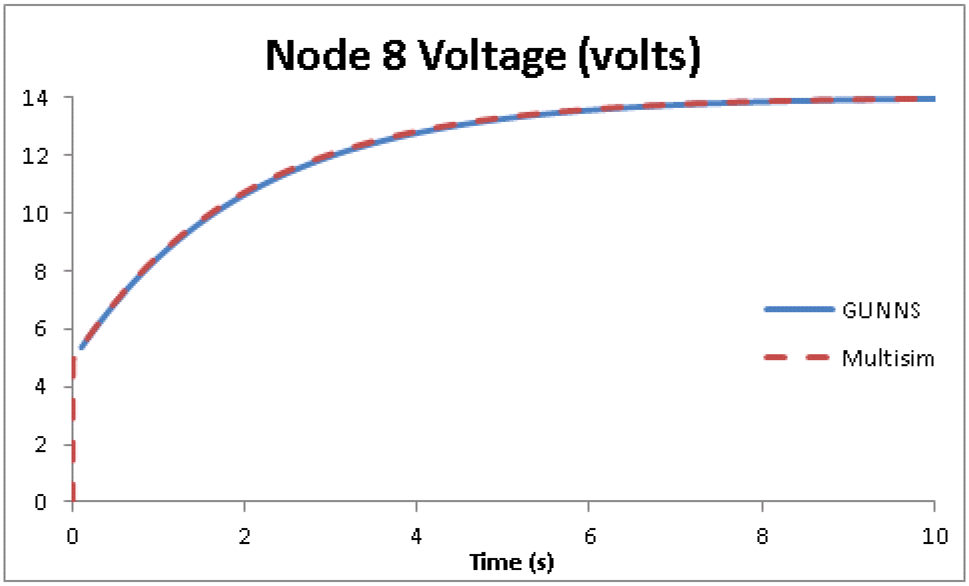


Figure 3-11: Node 8 Voltage.

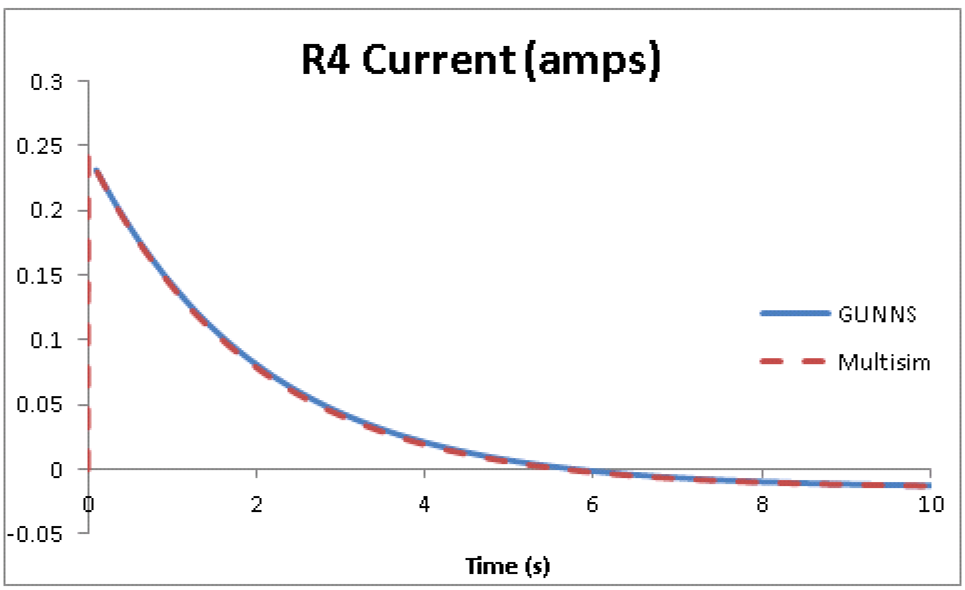


Figure 3-12: R4 Current.

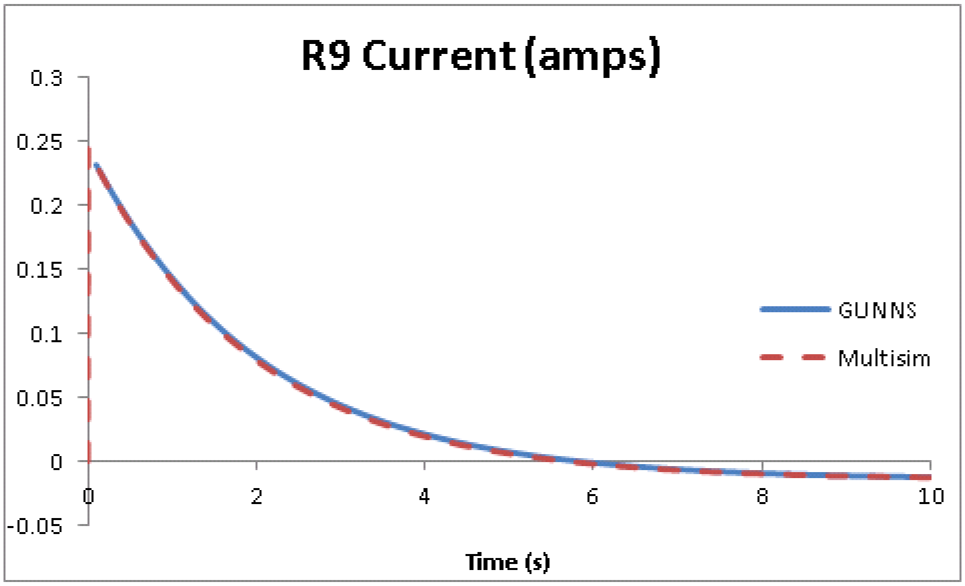


Figure 3-13: R9 Current.

3.4 Test 4

We present a comparison of an ideal diode, a real diode, and a real diode equivalent network.

Figure 3-14 compares the output voltage of the different diodes using the NI Multisim software.

From this test, we observe that the real diode and real diode equivalent network produce very similar results. Differences between ideal and real diodes are discussed in Section 4.

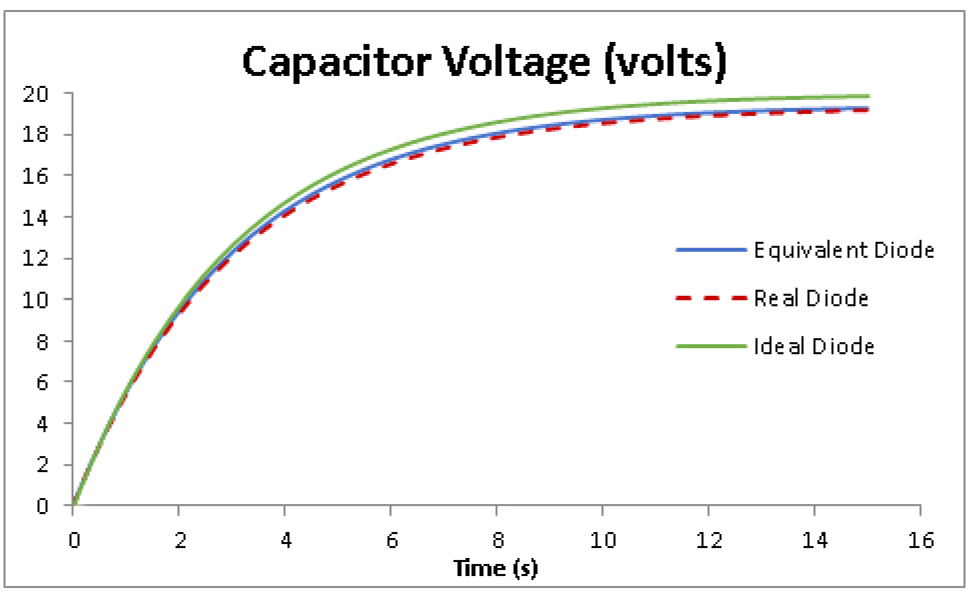


Figure 3-14: Capacitor Voltage.

3.5 Test 5

We present a comparison of a single cell solar array to its equivalent circuit in both the model and NI Multisim.

The figures below compare the output voltage and current of the single cell solar array to its equivalent circuit in both the model and NI Multisim. From this test, we observe that the GUNNS model and NI Multisim model are very similar. We note a spike in GUNNS C1 current around time = 2 seconds. This discrepancy is discussed in Section 4.

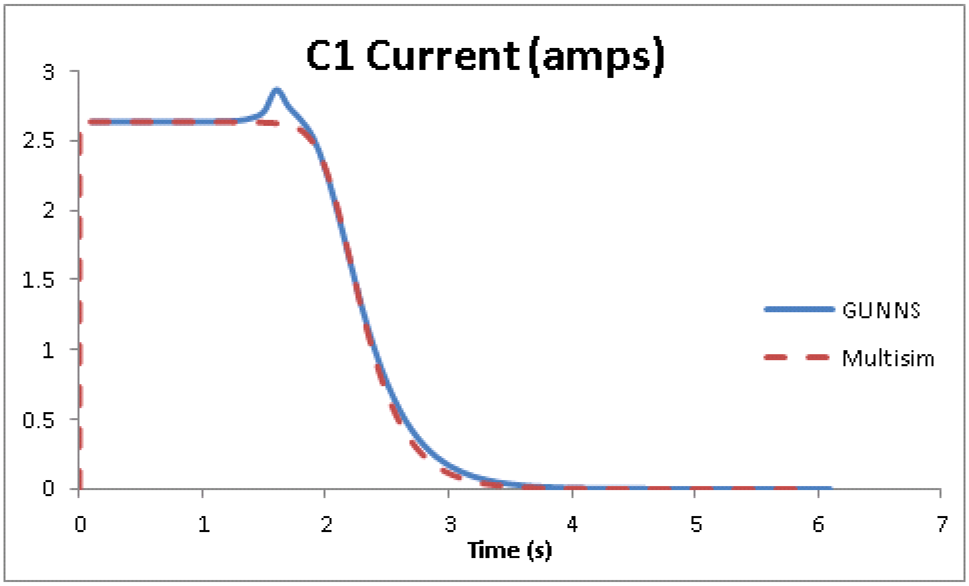


Figure 3-15: Comparison of Capacitor Voltage for Solar Cell.

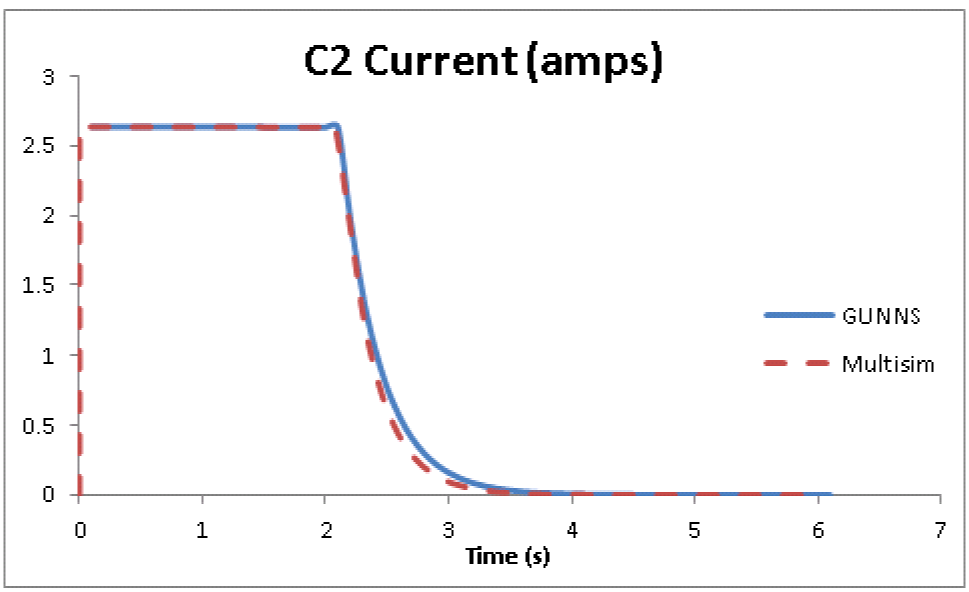


Figure 3-16: Comparison of Capacitor Voltage for Equivalent Circuit

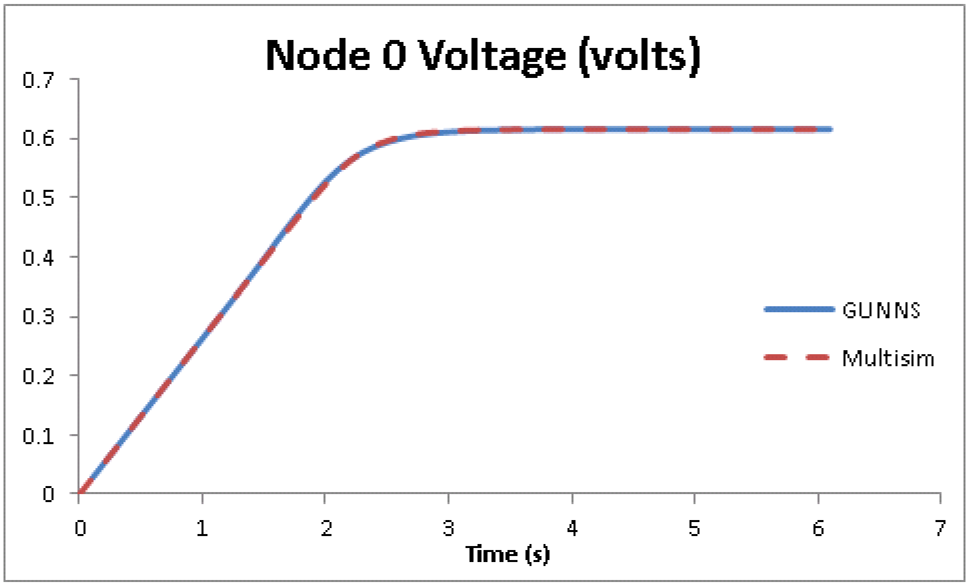


Figure 3-17: Comparison of Node Voltage for Solar Cell.

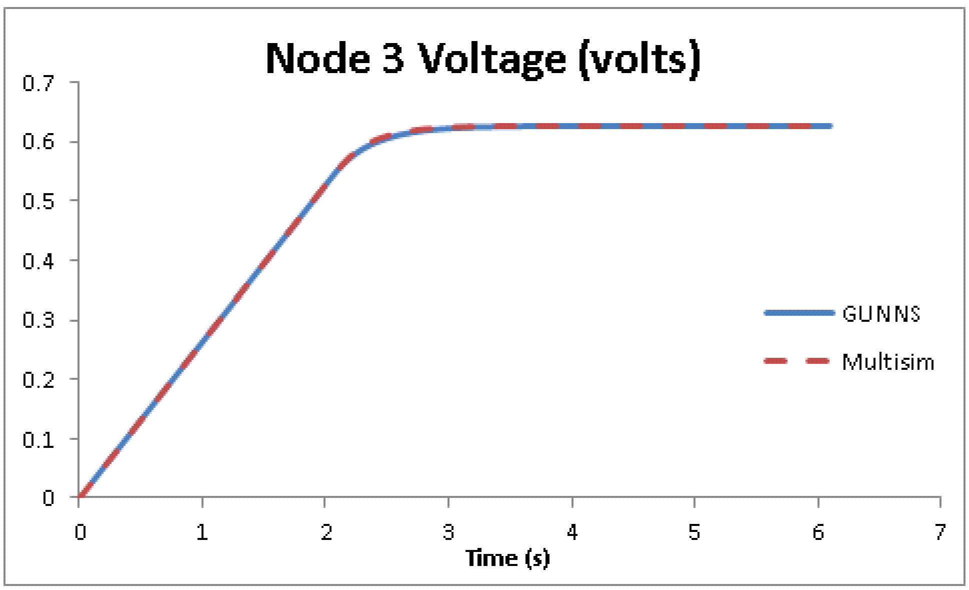


Figure 3-18: Comparison of Node Voltage for Equivalent Circuit.

3.6 Test 6

We present a comparison of a multiple cell solar array to its equivalent circuit in both the model and NI Multisim.

The figures below compare the output voltage and current of the networks in both the model and NI Multisim. Discrepancies in the output data are discussed in Section 4.

From this test, we observe that the GUNNS model and NI Multisim model are very similar. We contribute the differences in the C1 current curve to the slight differences in the solar array model in GUNNS and NI Multisim.

However, we see that this difference in the C1 current curve has little impact on changing the other curves.

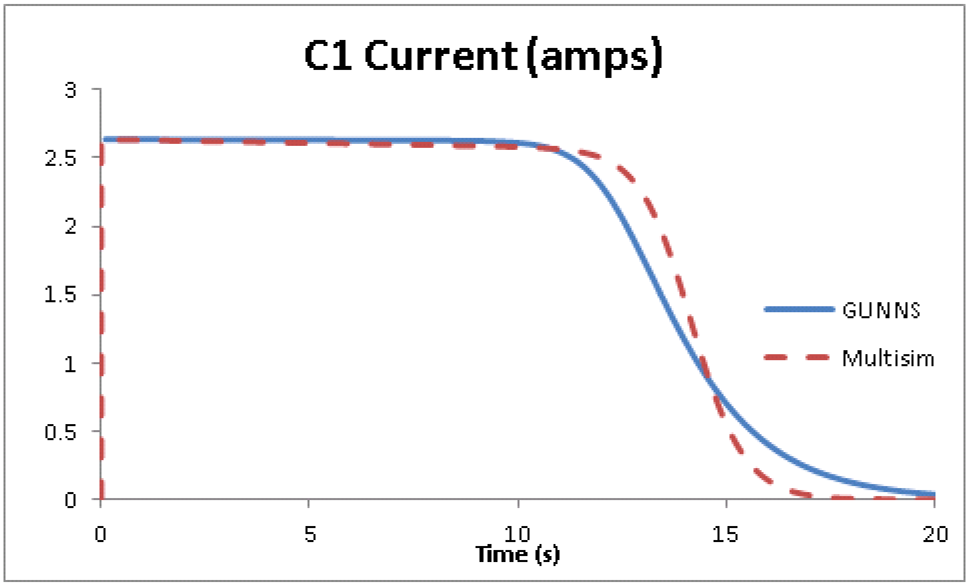


Figure 3-19: Comparison of Capacitor Voltage for Solar Array.

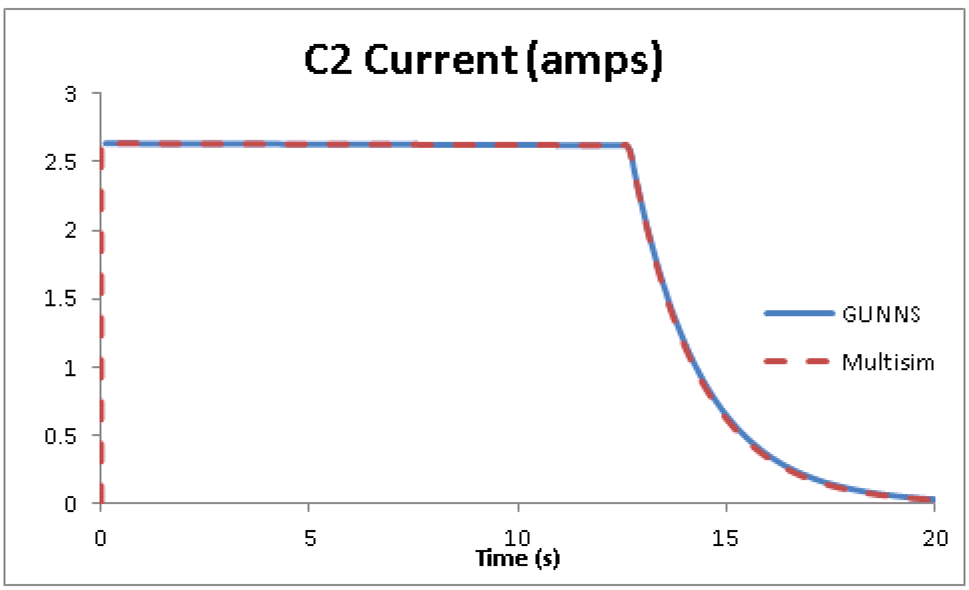


Figure 3-20: Comparison of Capacitor Voltage for Equivalent Circuit

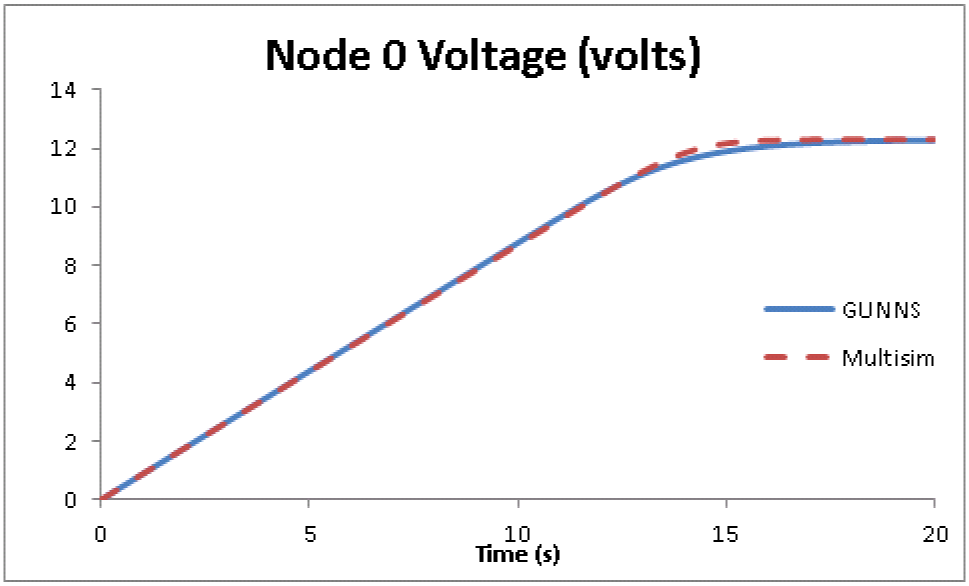


Figure 3-21: Comparison of Node Voltage for Solar Array.

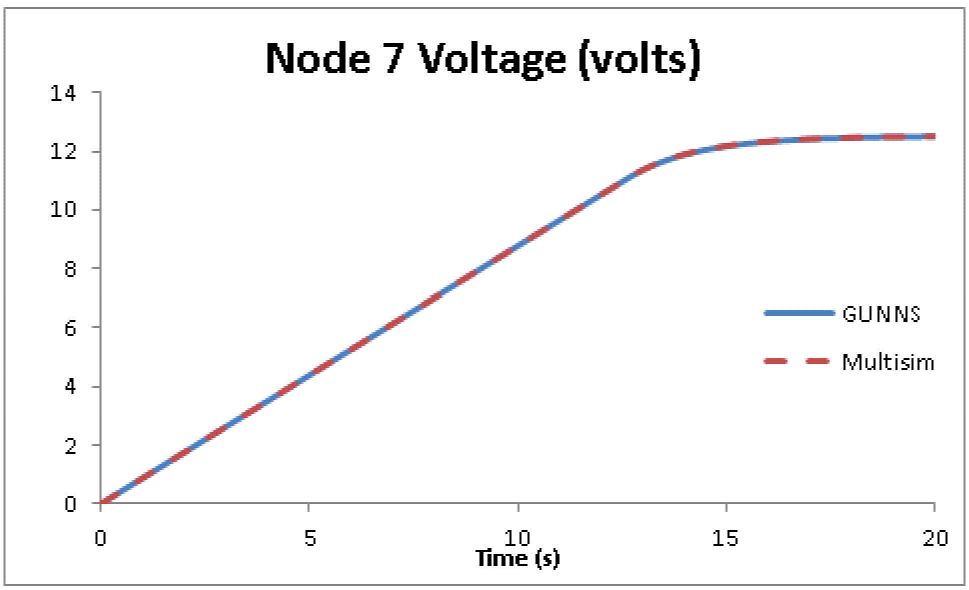


Figure 3-22: Comparison of Node Voltage for Equivalent Circuit.

3.7 Test 7

We present a comparison of an electrical converter and solar array regulator in both the model and NI Multisim.

The figures below compare the output voltage, output current, and power of the networks in both the model and NI Multisim.

We observe many differences in Test 7 between NI Multisim and GUNNS. These differences are discussed in Section 4.

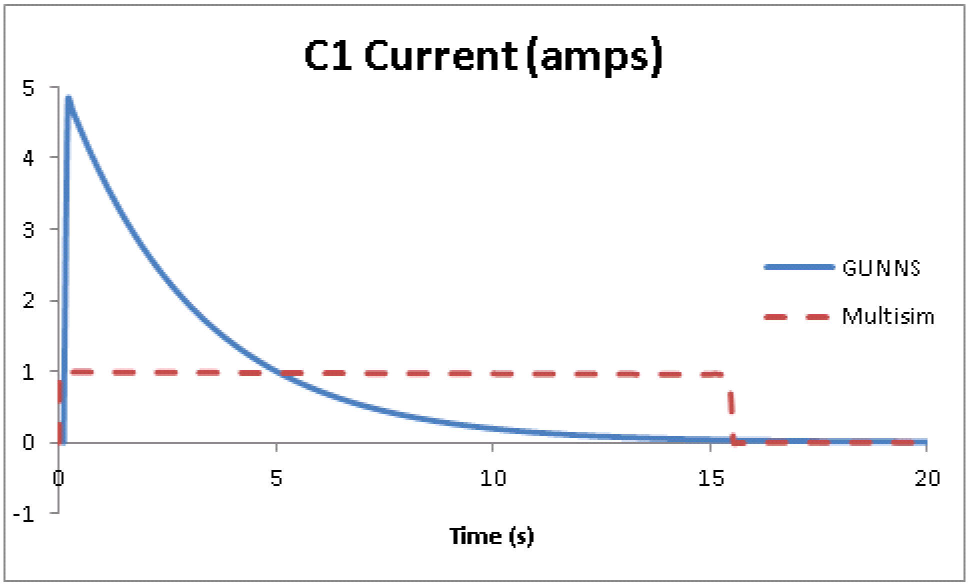


Figure 3-23: C1 Current.

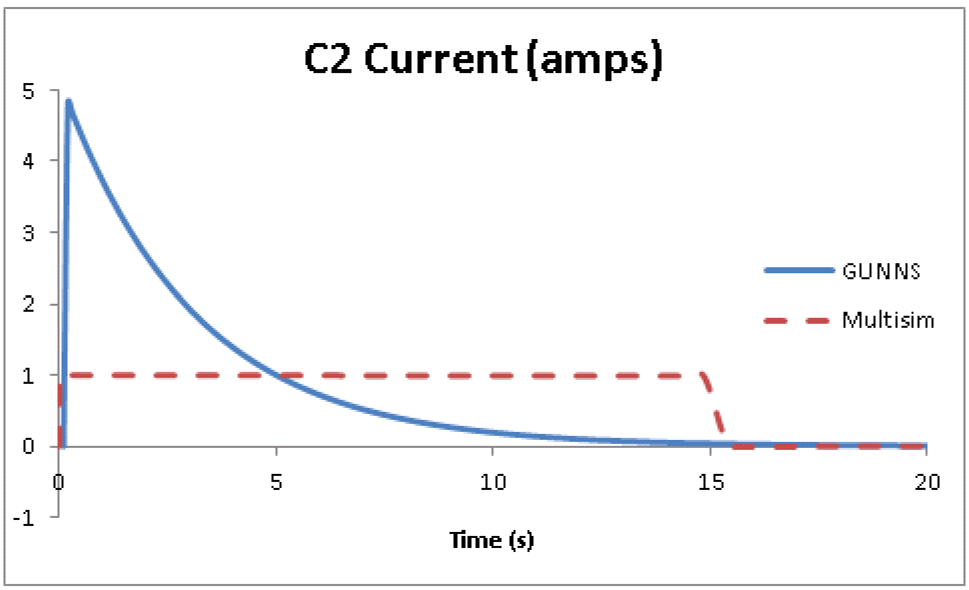


Figure 3-24: C2 Current.

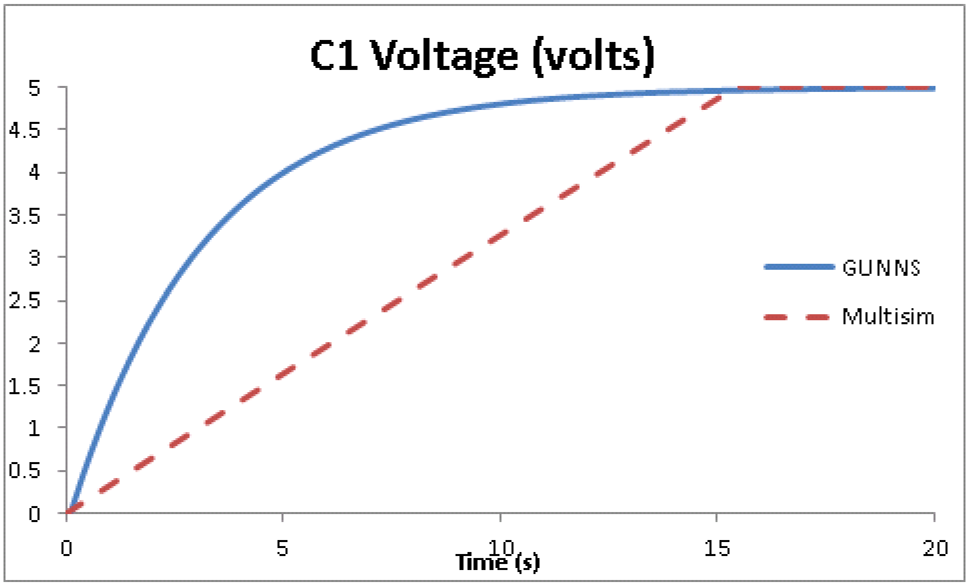


Figure 3-25: C1 Voltage.

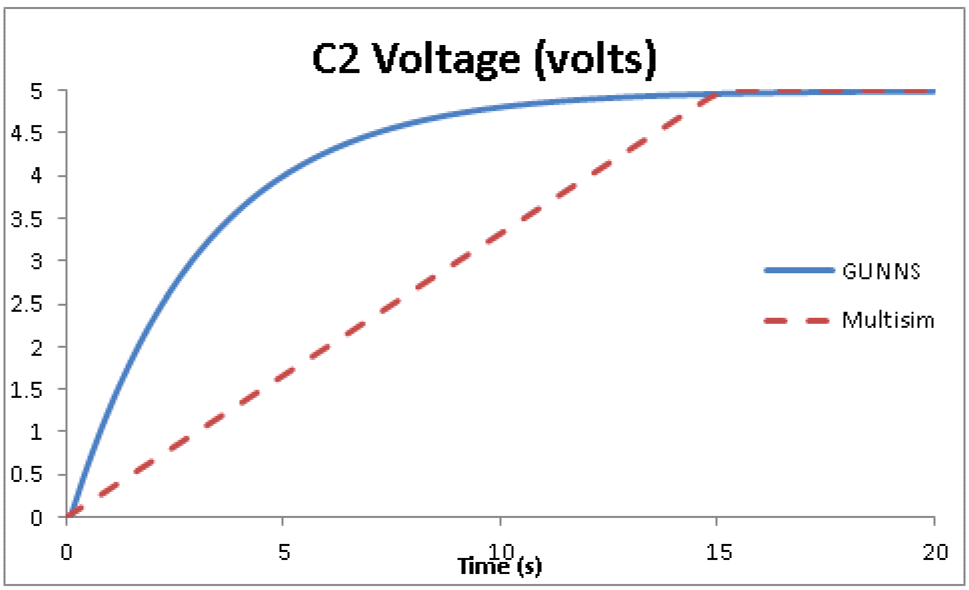


Figure 3-26: C2 Voltage.

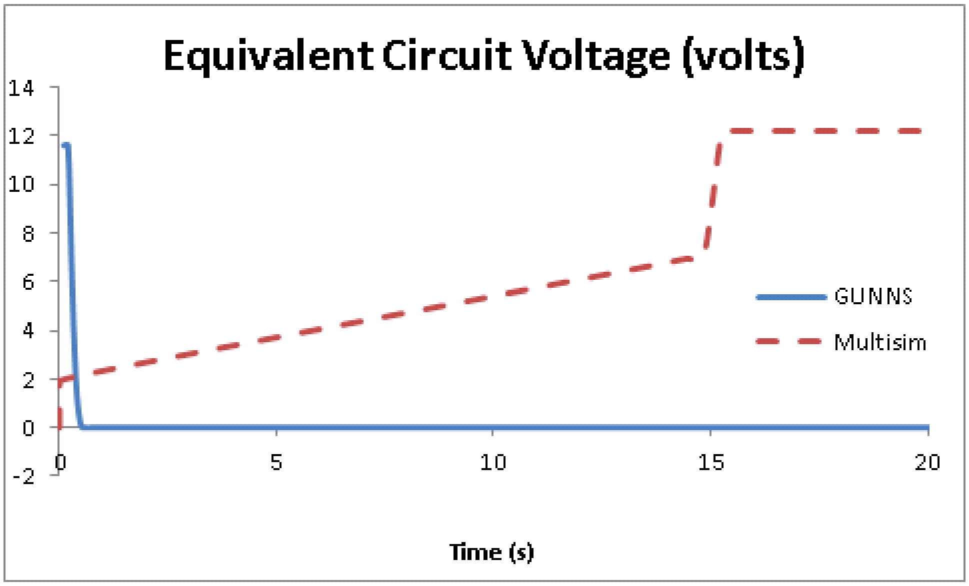


Figure 3-27: Equivalent Circuit Voltage.

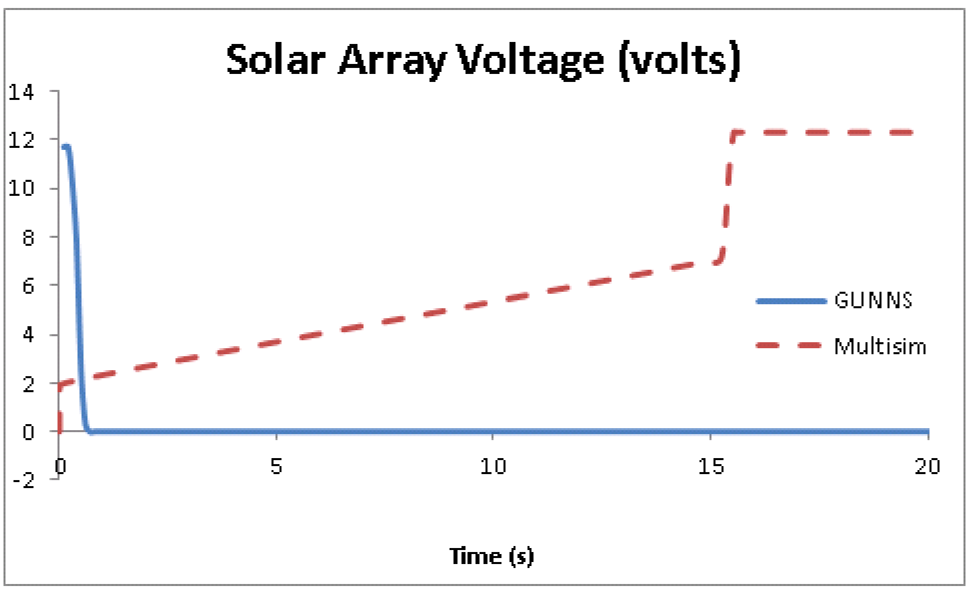


Figure 3-28: Solar Array Voltage.

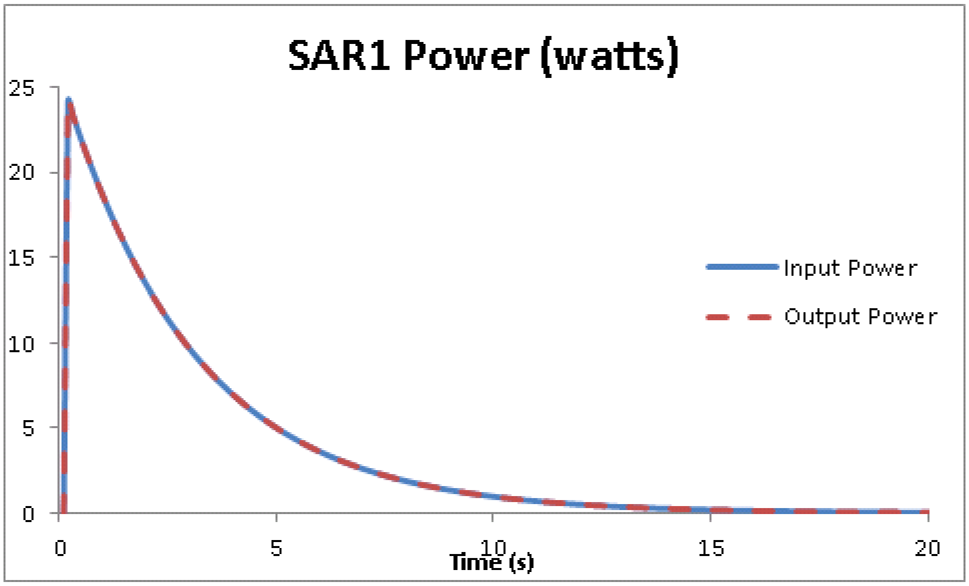


Figure 3-29: SAR1 Input and Output Power.

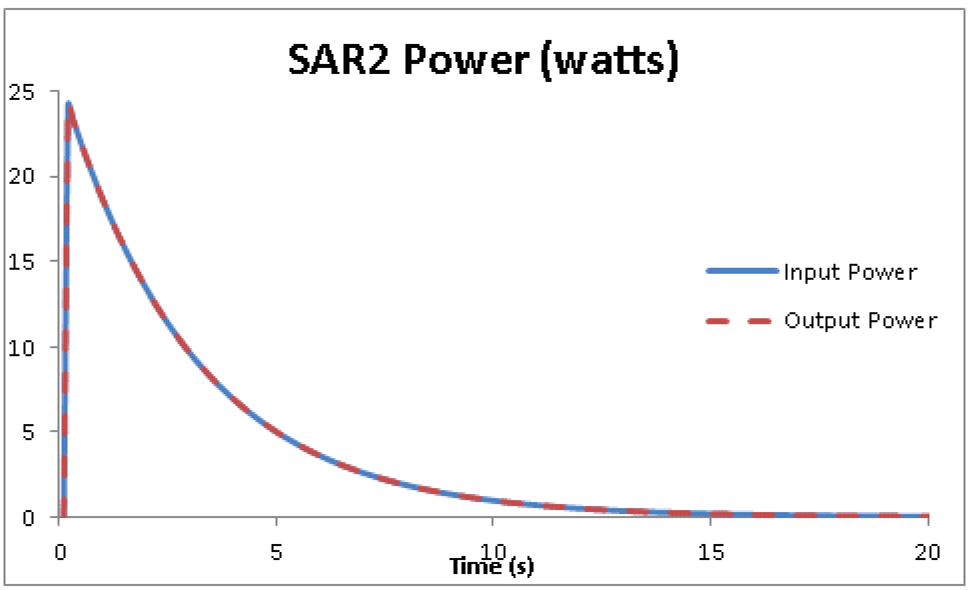


Figure 3-30: SAR2 Input and Output Power.

4. Discrepancies and Recommendations

In this section, we take a closer look at the discrepancies between the GUNNS, hardware, and NI Multisim data and explain their causes. Based on this analysis, we suggest improvements or workarounds to GUNNS to mitigate some of the discrepancies.

4.1 All Tests: Trick Log Time Limitation

GUNNS networks are updated in run-time inside Trick ”scheduled” jobs. A Trick limitation involving when simulation time is updated relative to when the scheduled jobs are run causes a discrepancy in the time tag that is logged for model output values. This limitation and its workarounds are discussed in detail in the GUNNS Wiki at: https://tricklab.jsc.nasa.gov/redmine/projects/gunns/wiki/InTRICKacies

Since the time error is exactly one frame of the scheduled job and its cause is known to not be an issue with GUNNS, we can correct it in our logged data. Since our GUNNS model update rates were always 10 Hz, we corrected the times by 0.1 seconds in all of our logged GUNNS data.

Figure 4-1 shows how the discrepancy, if left uncorrected, would affect our comparison data. Compare this to Figure 3-17, which is the same data but with the time correction applied.

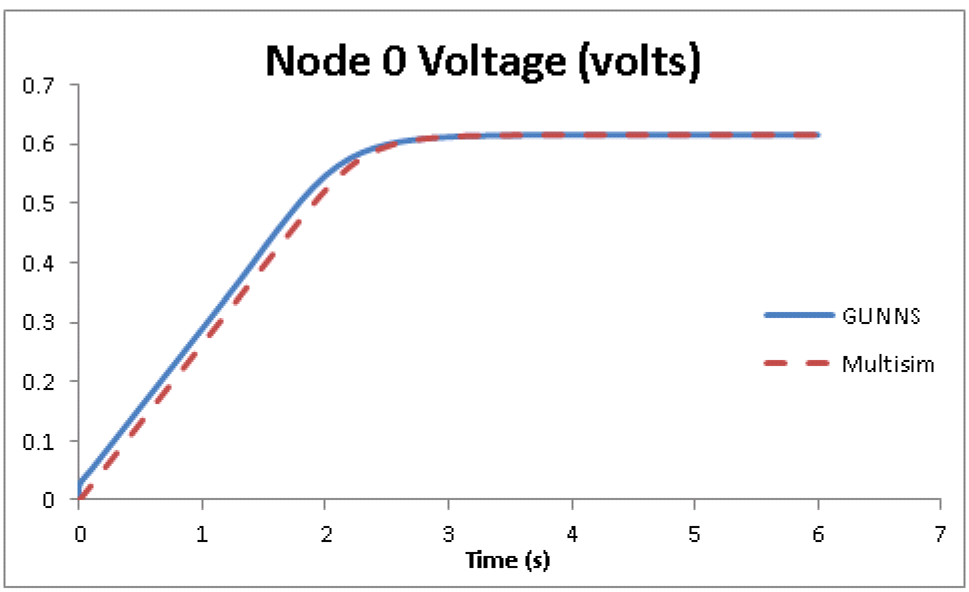


Figure 4-1: Node 0 Voltage With Un-corrected Time Step.

4.2 Test 1: Capacitance and Discretization Error

In Figures 3-1 and 3-2 we observed a slight discrepancy in the voltage when the capacitor is charging. We can attribute this error to two causes:

- A difference between the rated and actual capacitance of the physical capacitor. This is possible since we did not measure the actual value.
- Integration error in GUNNS due to its finite execution rate. This is a known and common limitation of software simulations in general.

4.3 Ideal Diode vs Real Diode

While NI Multisim can provide ideal and real diode components, GUNNS only provides ideal diodes. Both ideal and real diodes accomplish the same task of allowing current to flow in only one direction, but there are some key differences. Real diodes are made of a semiconducting material, which has a p-n junction. The ”p” side contains electron holes, while the ”n” side contains electrons, with a depletion region where no charge carriers exist between the two sides. From this physical characteristic, a certain voltage level is required in order for current to flow across the diode, which is typically 0.6-0.7 volts for a silicon diode. This required voltage depends on the diode material, the amount of current flowing through the diode, and temperature. NI Multisim models some of these effects in its real diode model, but the GUNNS ideal diode model does not.

In our tests, this GUNNS limitation was worked around by adding an opposing voltage source in series with the ideal diode. This models a linear voltage drop, which is very close to what a real diode exhibits due to its physical properties. The effectiveness of this workaround was verified in Test 4.

To diminish discrepancies, we recommend the following:

- Implement a Real Diode link in GUNNS that models the voltage drop required for current to flow across the diode.
- Legacy model developers may consider upgrading their models to the Real Diode link.
- Alternatively, model developers may consider upgrading their models with the voltage source workaround demonstrated in these tests.

4.4 Test 5 Solar Array Current Spike

In Test 5, we observe that the GUNNS solar array network exhibits a small spike in the capacitor’s current before the expected decreases. We also observe that the equivalent circuit does not have the same current spike. The spike is due to the stability filter in the GUNNS solar array link used in the solar array network. This filter attempts to ensure that the solar array IV curve is met, while maintaining stability with the network solution. The filter has limitations in how fast it can respond to changing circuit conditions.

Therefore, we recommend:

- Investigate improving the stability filter to solve any convergence issues.
- Consider using the equivalent circuit instead for future endeavors.

4.5 GUNNS Voltage Regulator vs NI Multisim Solar Array Regulator

In Test 7, we used a LM7805 linear voltage regulator in Multisim, while GUNNS used a solar array regulator link to regulate the output voltage of the network. While there are other components that exist that regulate voltage, a linear voltage regulator was the closest equivalent to the solar array regulator link we could find in the Multisim library. While both components regulate the output voltage, they do so in different ways, which creates differences in the circuit response.

The LM7805 linear voltage regulator contains a transistor that acts as a variable resistor. Additionally, the LM7805 is designed to output 5V while maintaining equivalent input and output currents. Essentially, a feedback loop is used which adjusts the variable resistance in order to dissipate the difference in the input and output voltage of the regulator while keeping the input and output currents the same. Currents being equal, the higher input voltage means there is higher input power, which is dissipated as heat in the transistor and lost to the environment.

The solar array regulator link works a bit differently. It models a DC-DC converter using switching technology to increase or decrease an input voltage to a specified output value, whereas the linear voltage regulator can only decrease voltage. Also, this link conserves power, which allows for the input and output currents to change.

To summarize these differences:

- The LM7805 conserves current while the GUNNS solar array regulator conserves power.
- The LM7805 only upper-limits output voltage to a maximum value, but allows for it to drop below the maximum value.
- The solar array regulator controls the output voltage to a fixed value at all times.
- Both electrical components are valid but simulate fundamentally different hardware.

These differences in the regulators cause the differences we see in the capacitor current and voltage in Test 7. The linear voltage regulator causes the current to be constant, which therefore results in the capacitor voltage to increase linearly. The solar array regulator allows for changes in the current, so we observe the usual exponential voltage and current curves for the capacitors.

The regulator differences also cause the differences in the solar array and equivalent circuit voltages. For the NI Multisim linear voltage regulator, the voltage starts at about 2 volts, and increases linearly. This is due to the dropout voltage of the regulator, which is a certain amount of voltage that the regulator must be given in order to run properly. Since the output voltage of the network starts at 0, and the dropout voltage is about 2 volts in this case, the input voltage is 2 volts. The output voltage increases linearly, which causes the input voltage to increase linearly as well. Once the capacitor is fully charged, the output current falls to 0, and the input voltage is able to obtain its maximum value defined by the IV curve of the solar array.

In GUNNS, the input current to the solar array regulator starts near its maximum, which causes the input voltage to be near its minimum value according to the IV curve of the solar array. These input characteristics are necessary in order for power to be conserved on both sides of the regulator. The solar array regulator has no minimum operating voltage because of the link's conservation of power and switching technology. If the input voltage is lower than the wanted output voltage, then the input current increases in order to conserve power.

While we observe many differences between the NI Multisim and GUNNS regulator circuits, these differences are expected. This comparison is still useful in determining that the GUNNS solar array regulator is working properly. All of the output data corresponded to what we expected to observe. Most importantly, we show that the power at the input and output of the GUNNS solar array regulator is conserved.

In the future, if we wanted to have a closer comparison of the solar array regulator, we could:

- Design a regulator in NI Multisim that functions similar to the solar array regulator.
- Design a regulator in GUNNS that functions similar to the linear voltage regulator.

5. Conclusions

This document presents a validation of the electrical aspect of GUNNS against data collected from actual hardware circuits and software circuits modeled in a comparable COTS tool.

We have:

- Shown that the nodal analysis circuit solver at the heart of GUNNS produces accurate and trust-worthy results.
- Shown that the main GUNNS effects (potential, flux, capacitance, conductance) are solved for accurately.
- Shown that the typical execution frequency (10 Hz) of GUNNS networks adds insignificant integration errors.
- Validated the GUNNS models of common electrical circuit components.
- Shown that GUNNS can accurately predict real hardware circuit performance.
- Shown that GUNNS produces similar results as reputable COTS software used in industry.

This satisfies all of the validation objectives. Furthermore, the validaton of the nodal analysis and main GUNNS effects carries over as additional validation of the GUNNS fluid and thermal aspects, since they reuse these implementations.

While all of the validation objectives have been met, there are still discrepancies and recommendations. We recommend:

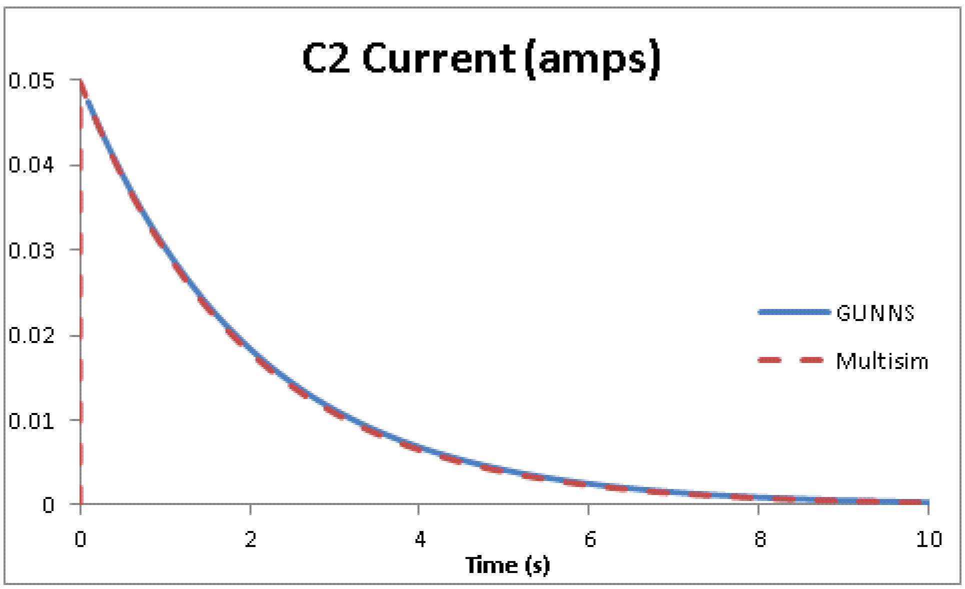
- Implementing a Real Diode link in GUNNS that models the voltage drop required for current to flow across the diode.
- Legacy users should consider using the Real Diode link or our linear voltage drop workaround.
- Design a regulator in GUNNS that functions similar to the linear voltage regulator. While there is no current need by any GUNNS users for this link, it would be able to improve the validation of Test 7.
- A follow-on effort to finish validating the remaining GUNNS links.

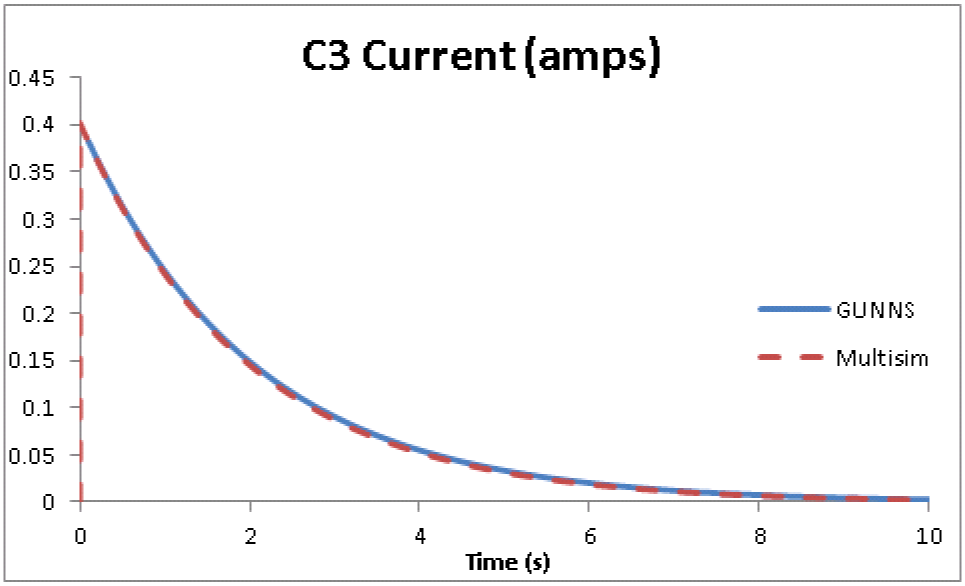
Appendices

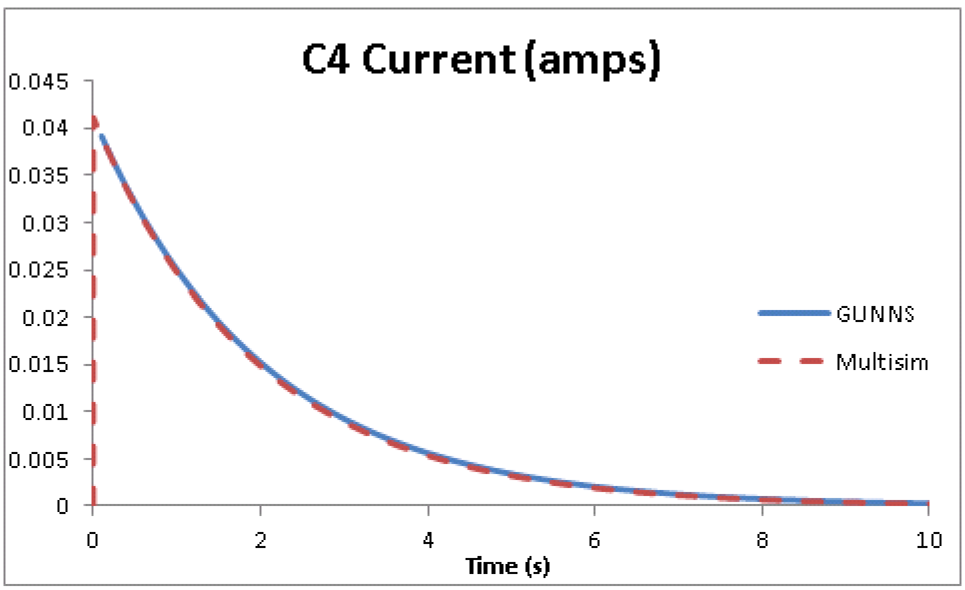
Appendix A

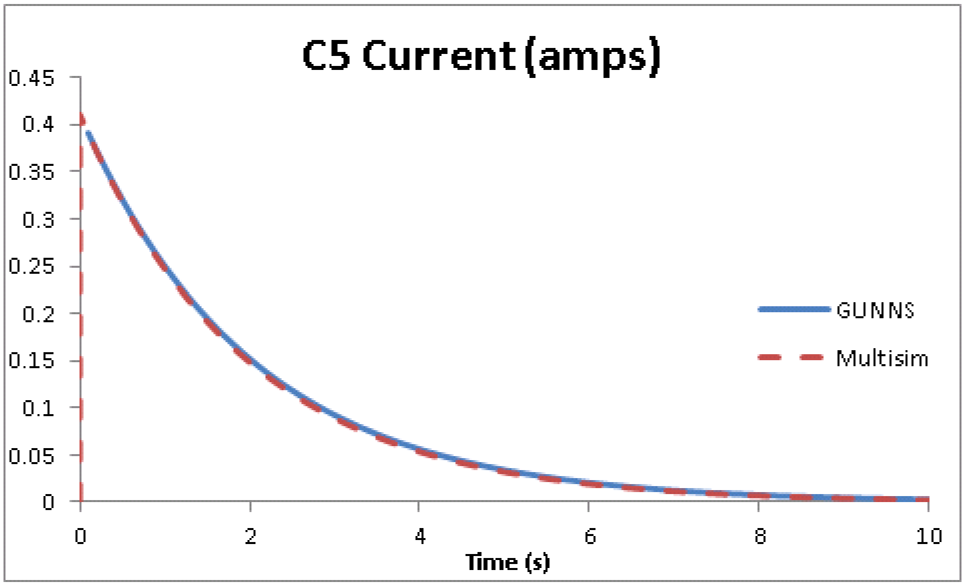
A.1 Test 3 Coplots

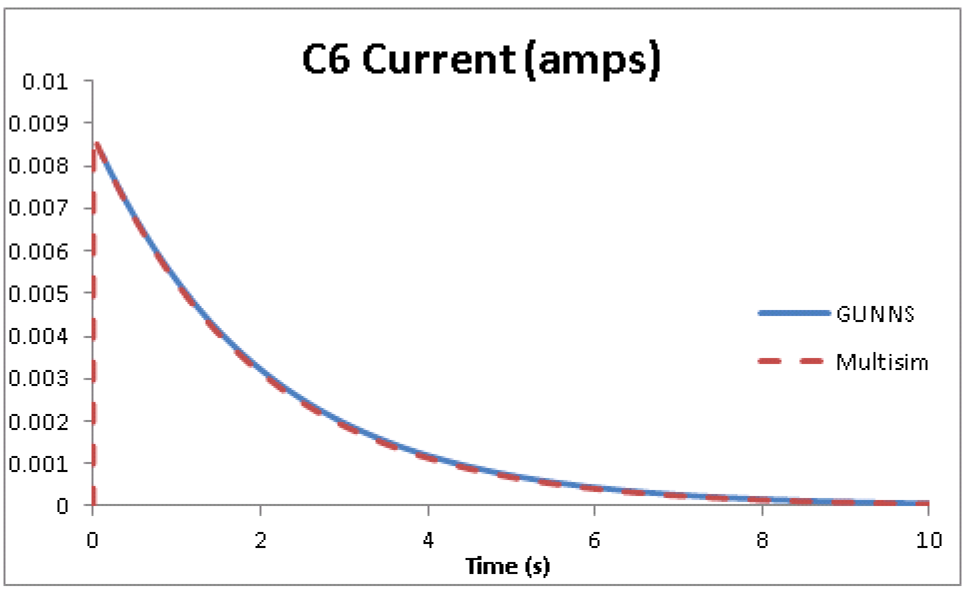
For reference, we present comparison plots between the model and software for Test 3 that were not used in Section 3.3:

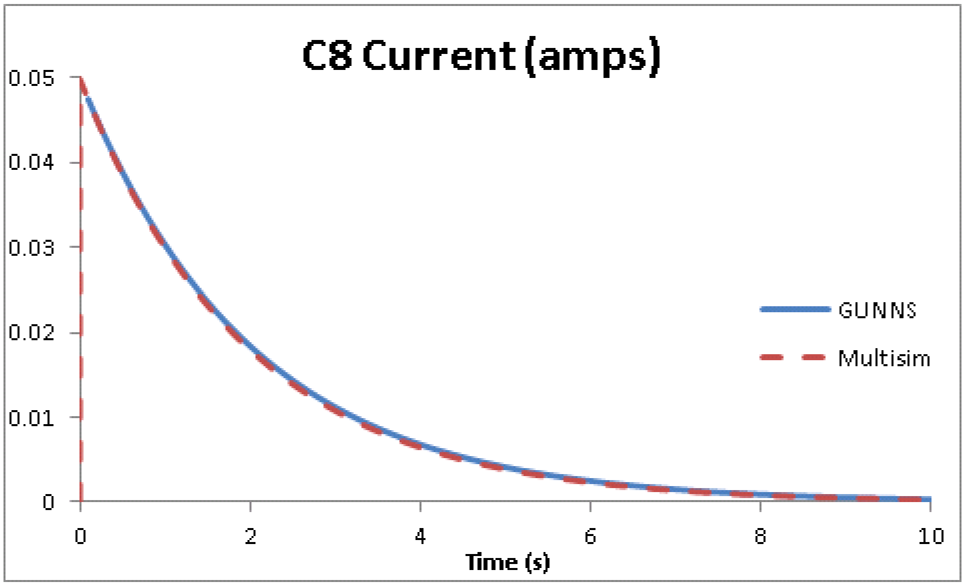


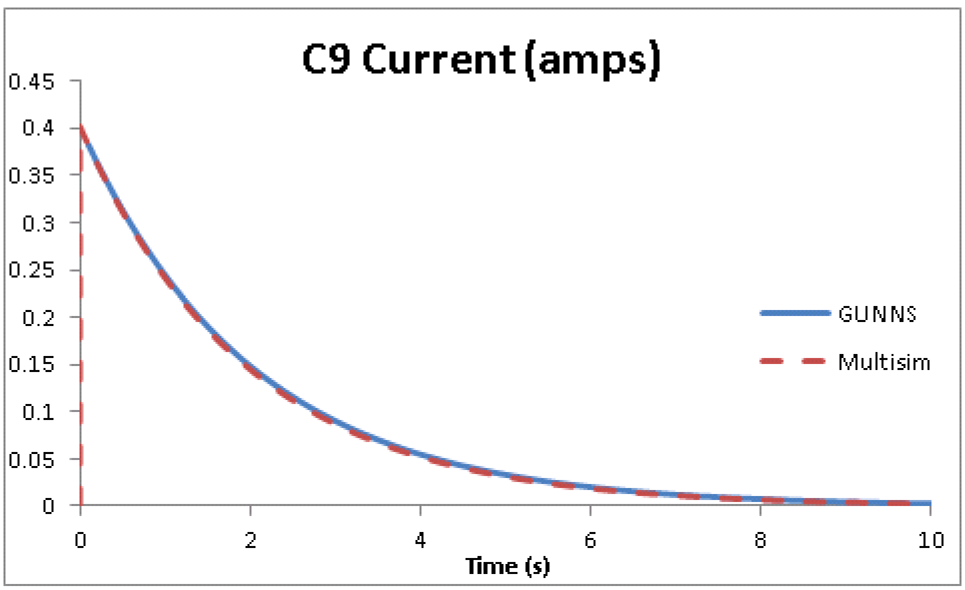

C3 Current (amps)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

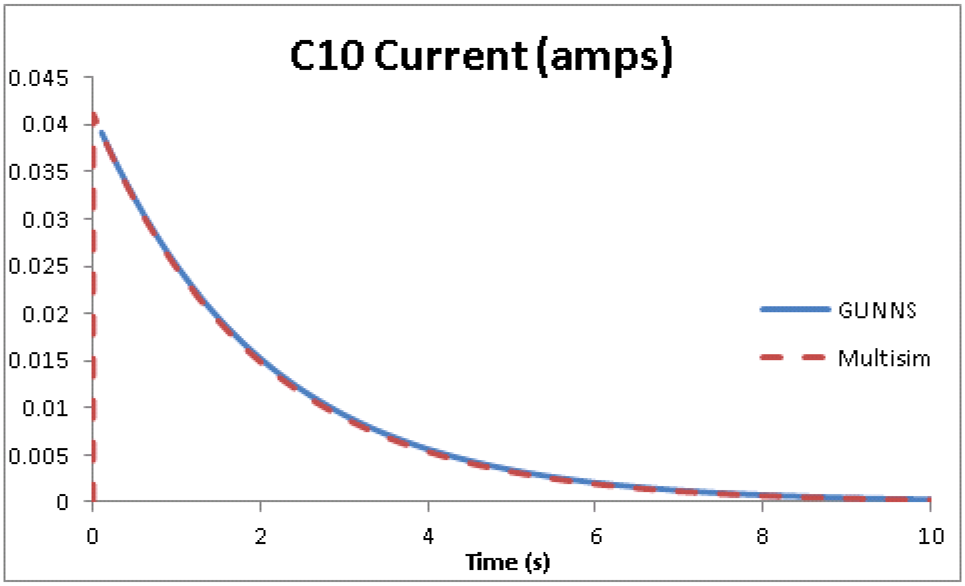

C4 Current (amps)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

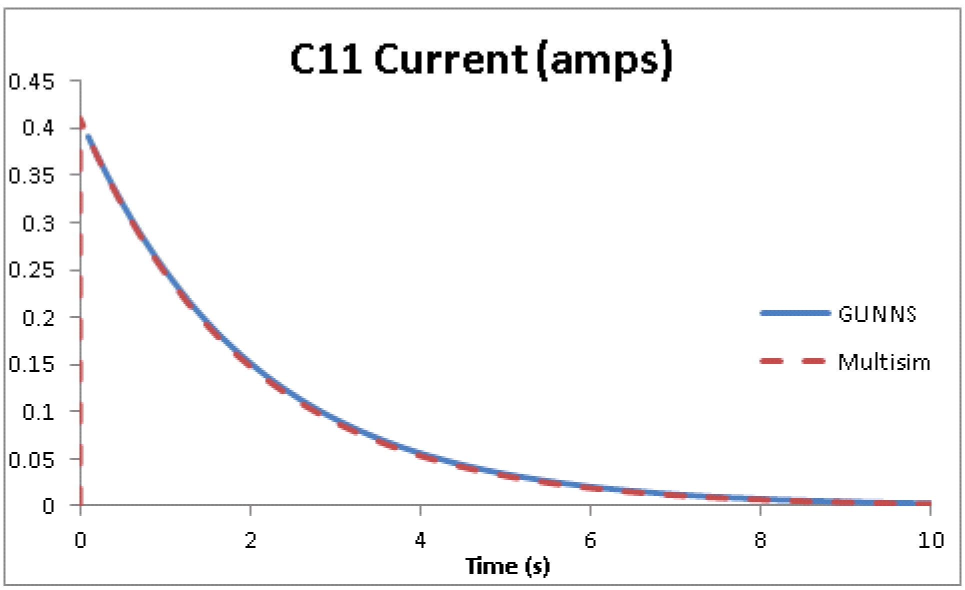

C5 Current (amps)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

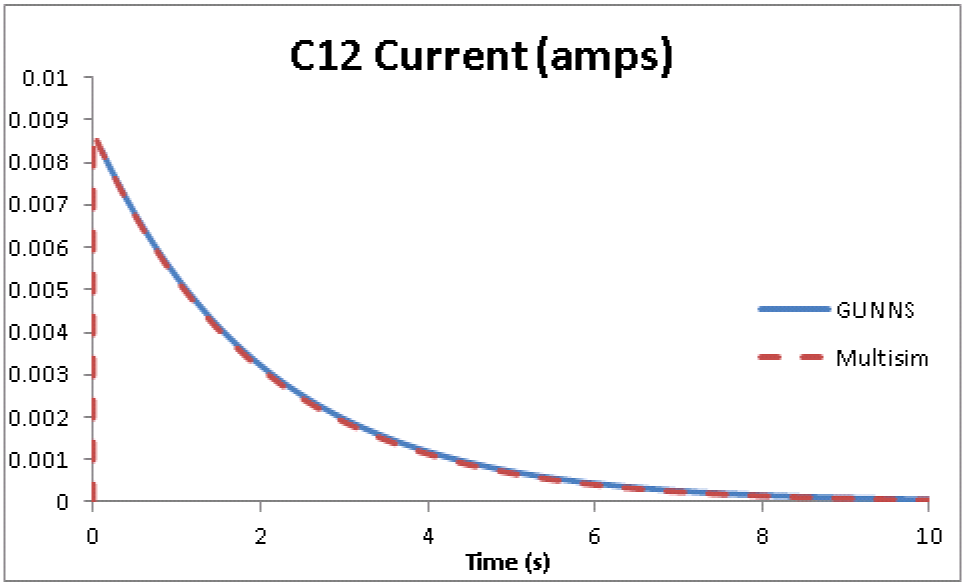

C6 Current (amps)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

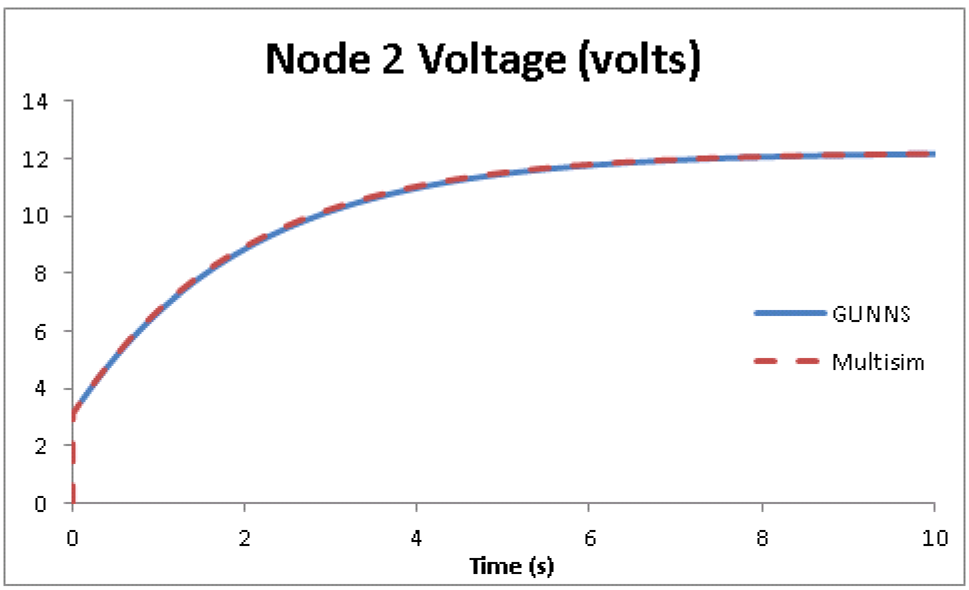

C8 Current (amps)
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

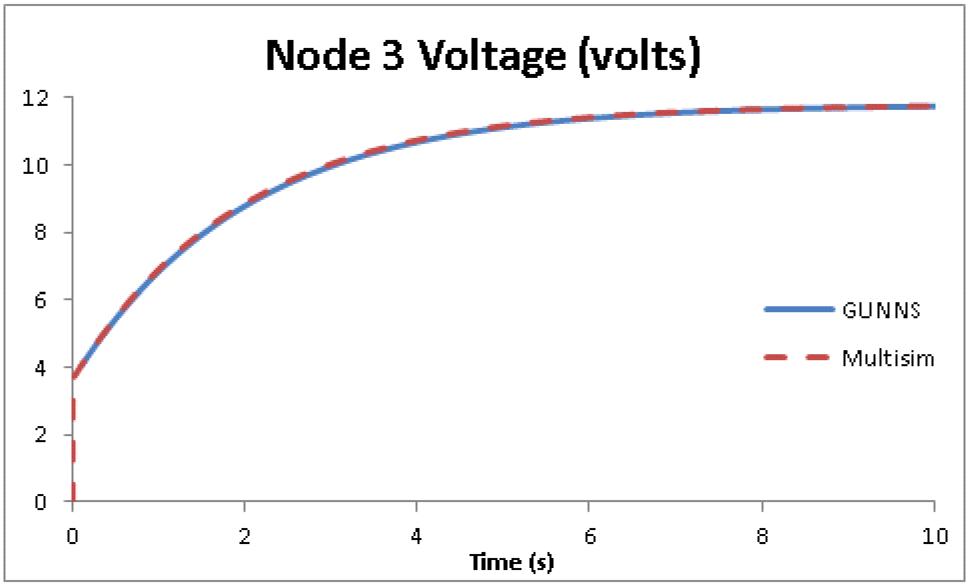

C9 Current (amps)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

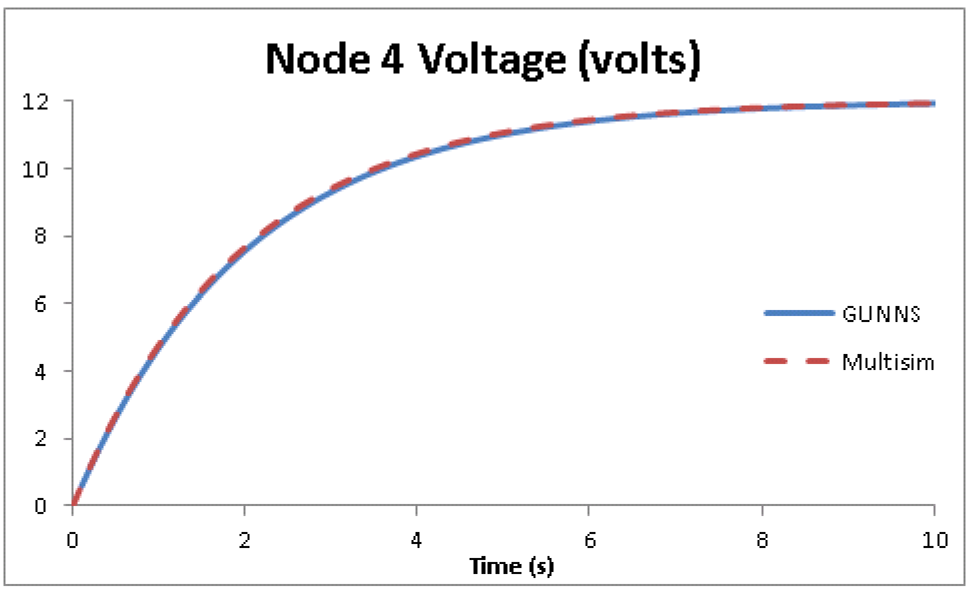

C10 Current (amps)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

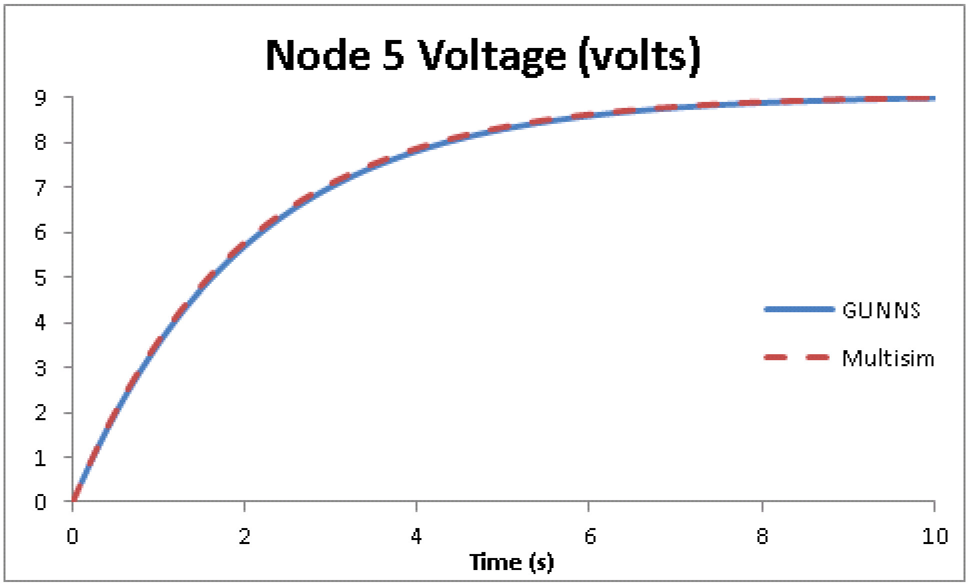

C11 Current (amps)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

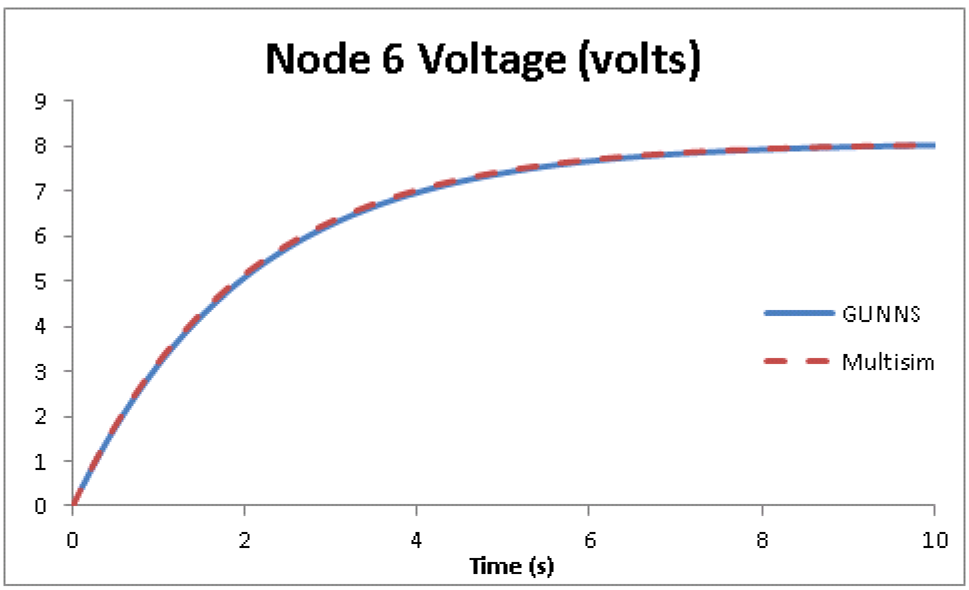

C12 Current (amps)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

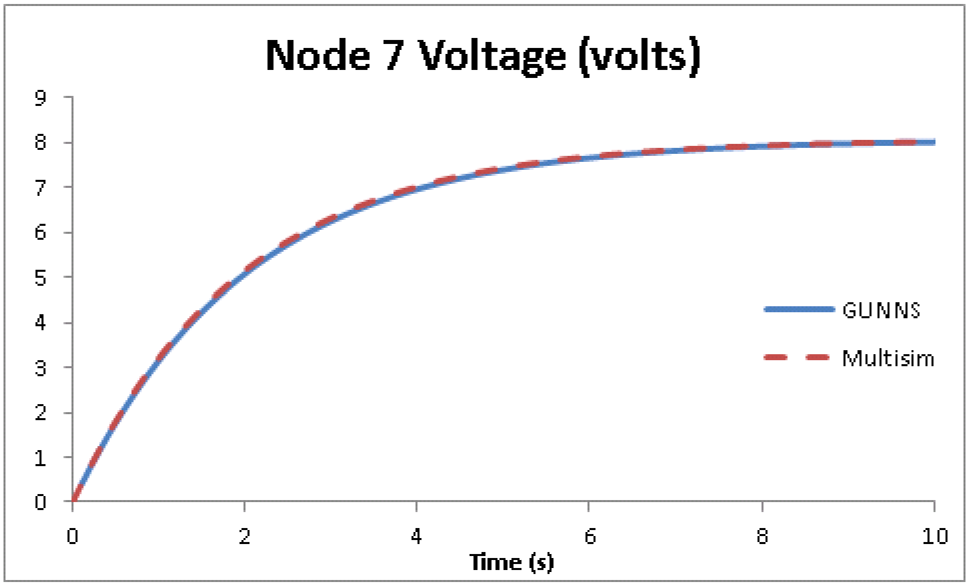

Node 2 Voltage (volts)
14
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

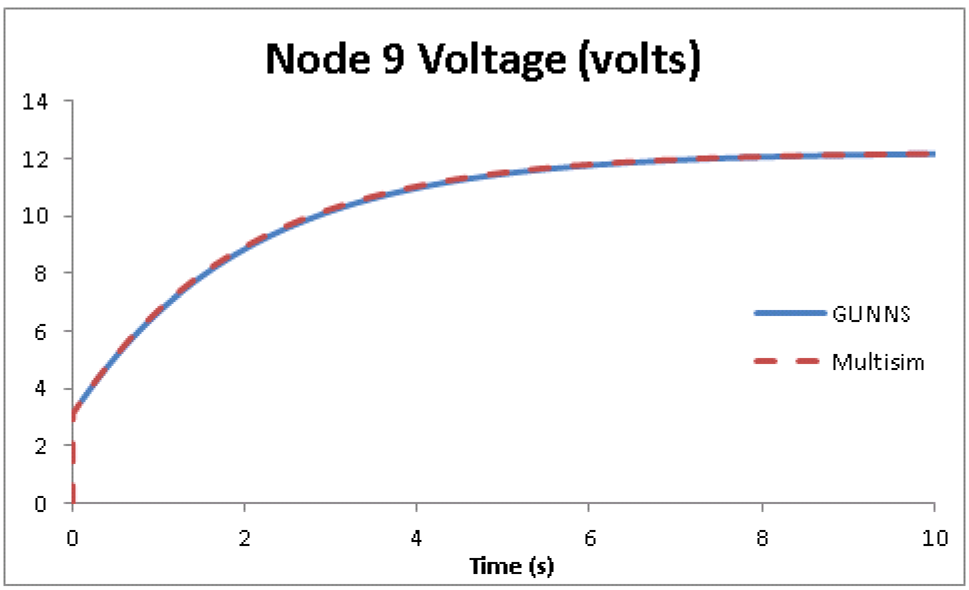

Node 3 Voltage (volts)
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

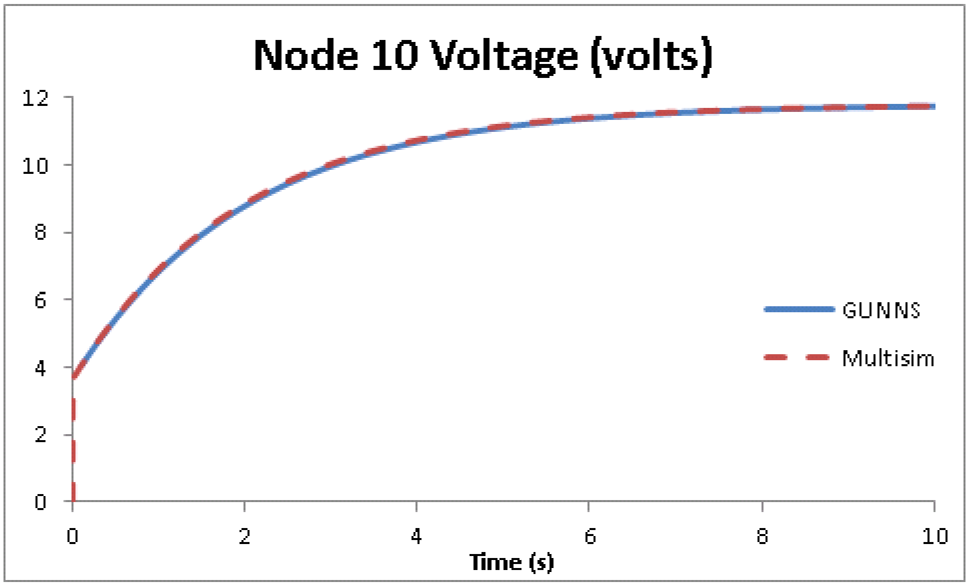

Node 4 Voltage (volts)
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

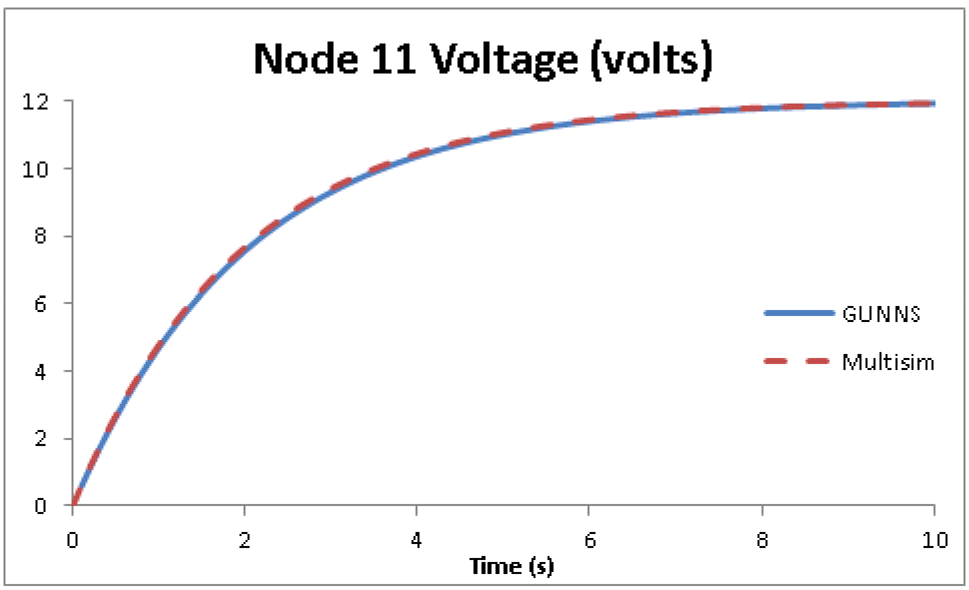

Node 5 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

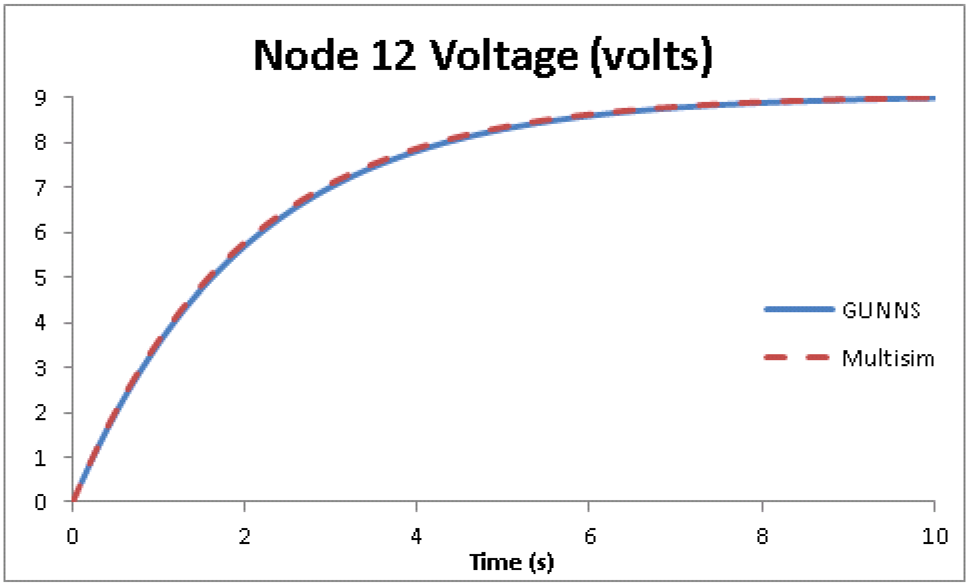

Node 6 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

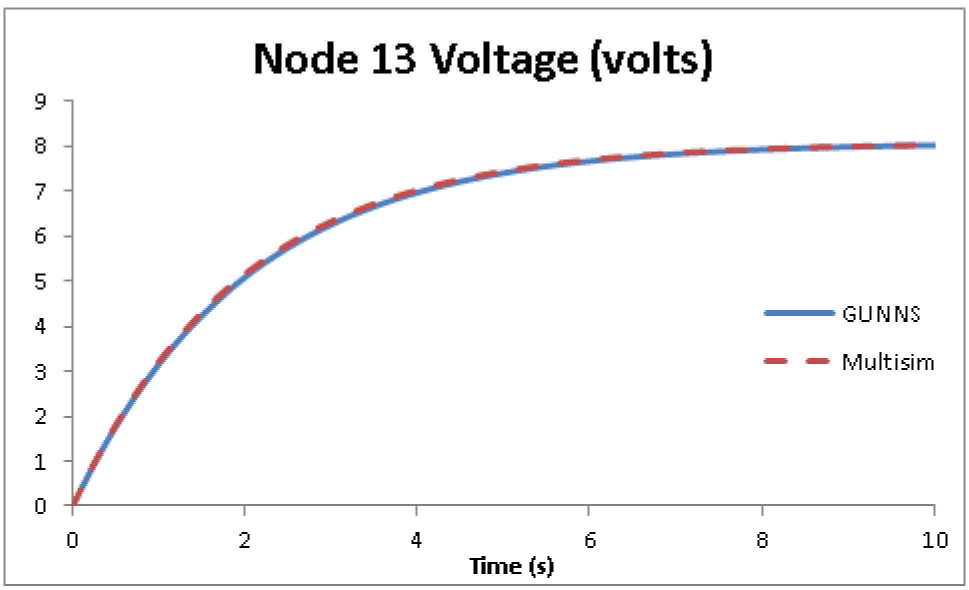

Node 7 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

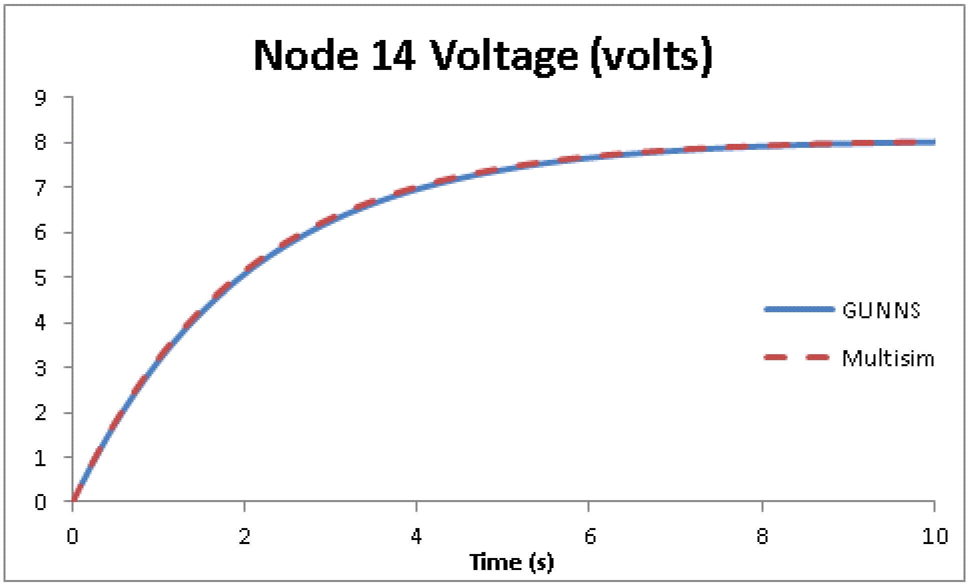

Node 9 Voltage (volts)
14
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

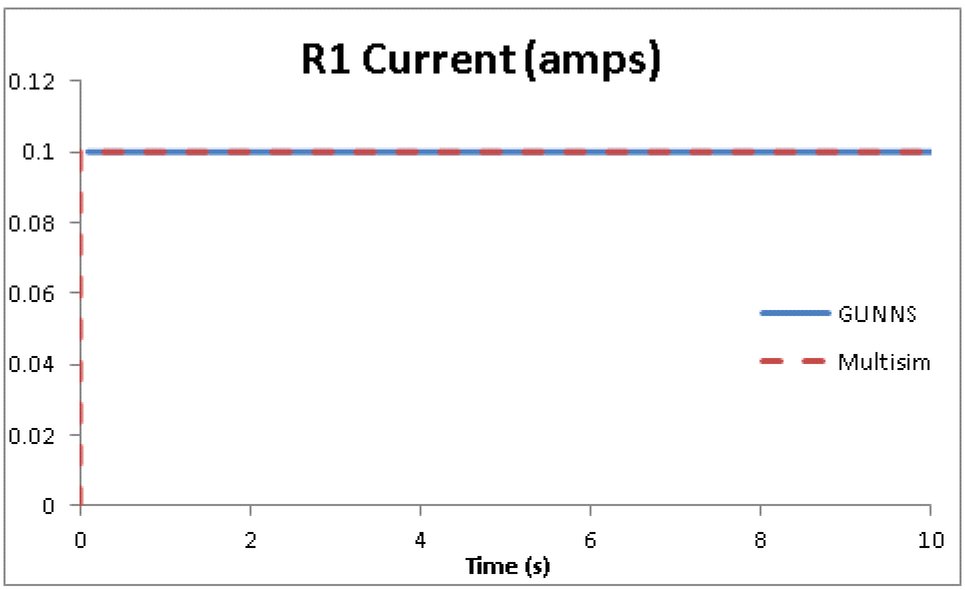

Node 10 Voltage (volts)
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

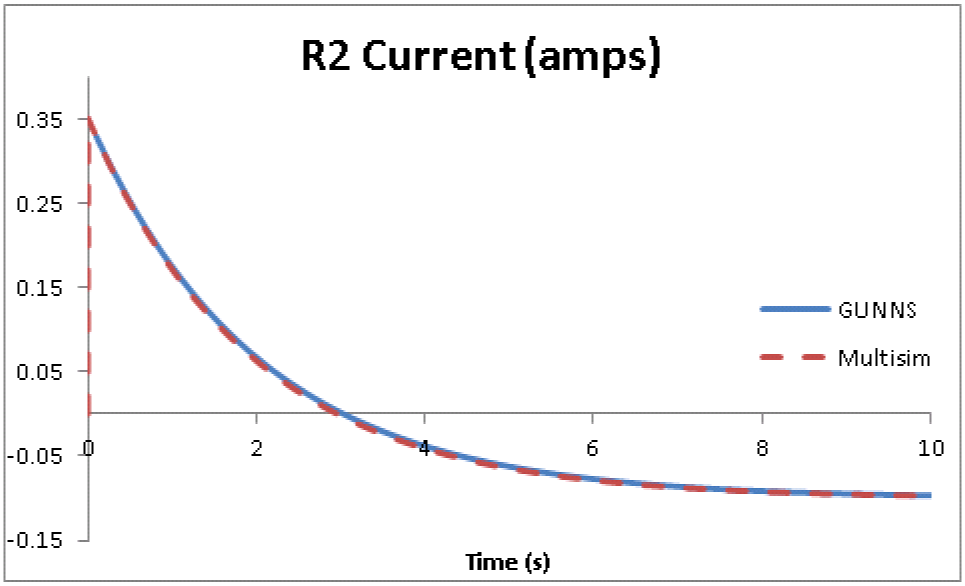

Node 11 Voltage (volts)
12
10
8
6
4
2
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

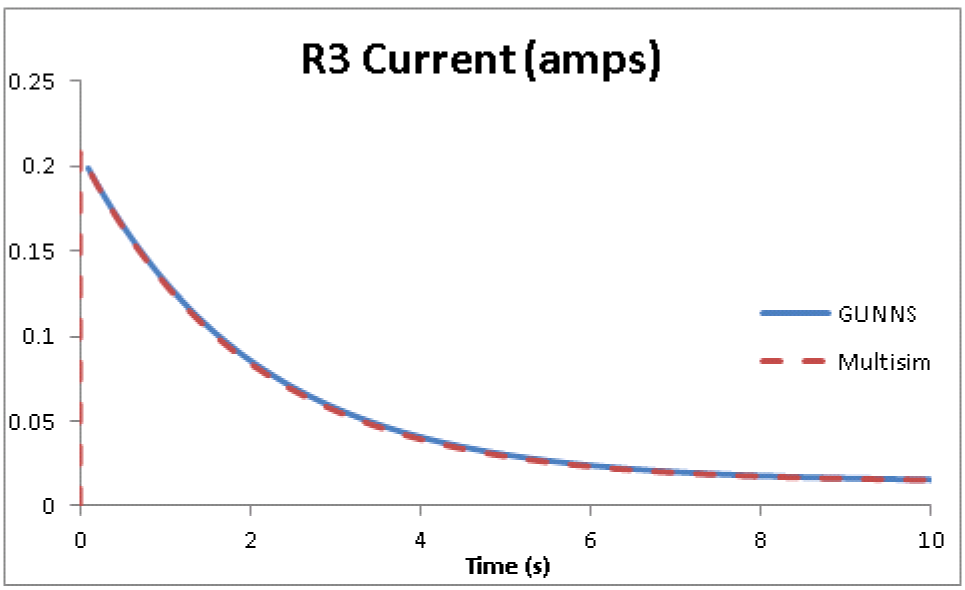

Node 12 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

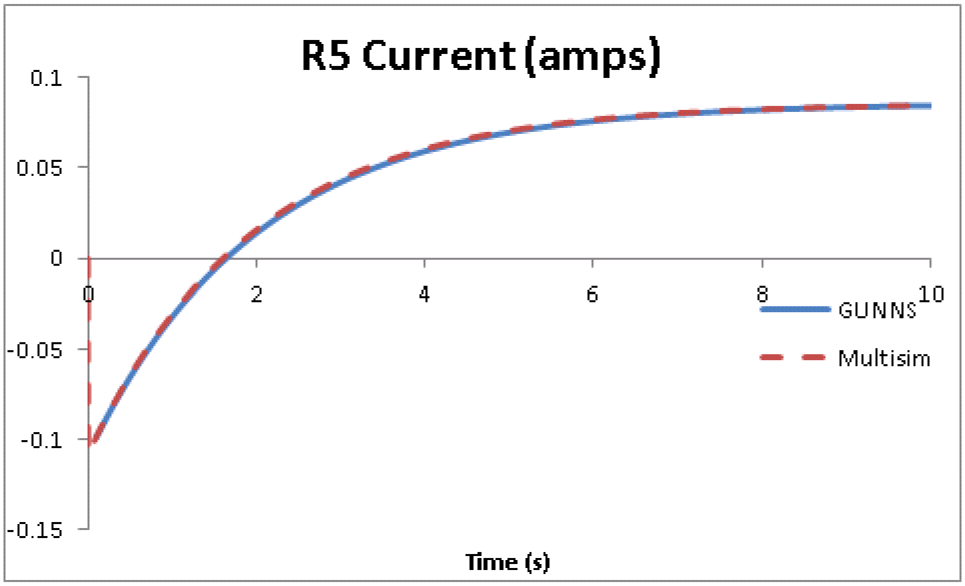

Node 13 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

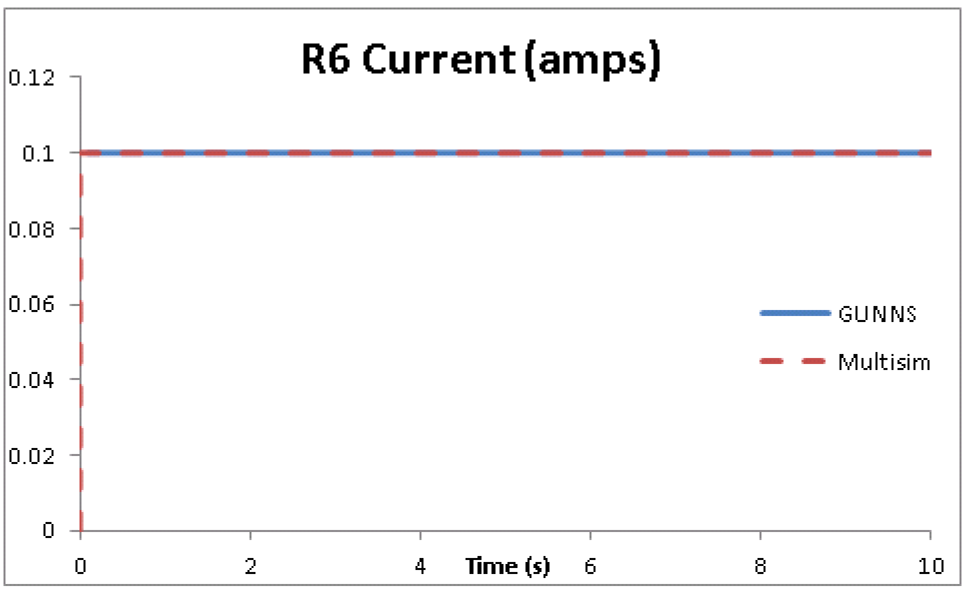

Node 14 Voltage (volts)
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

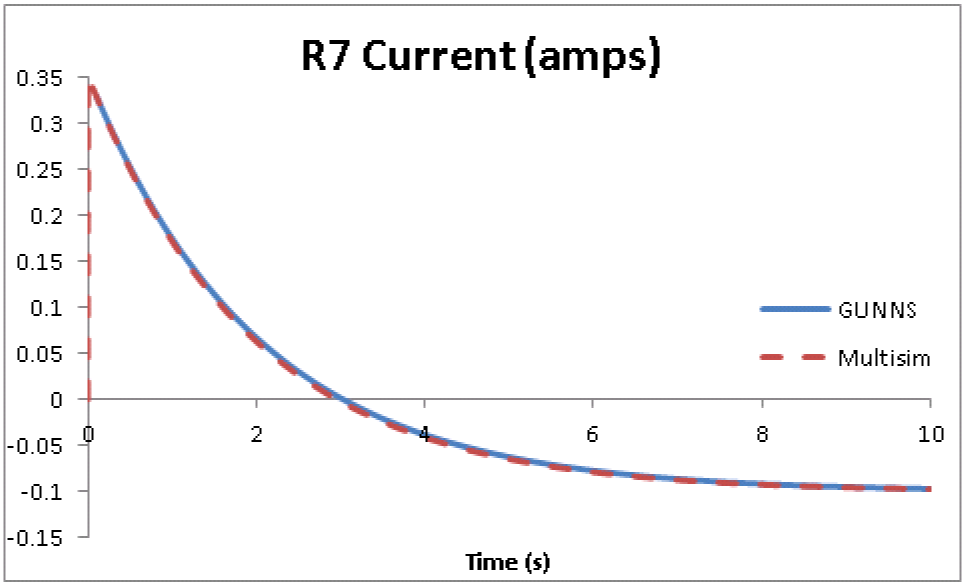

R1 Current (amps)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

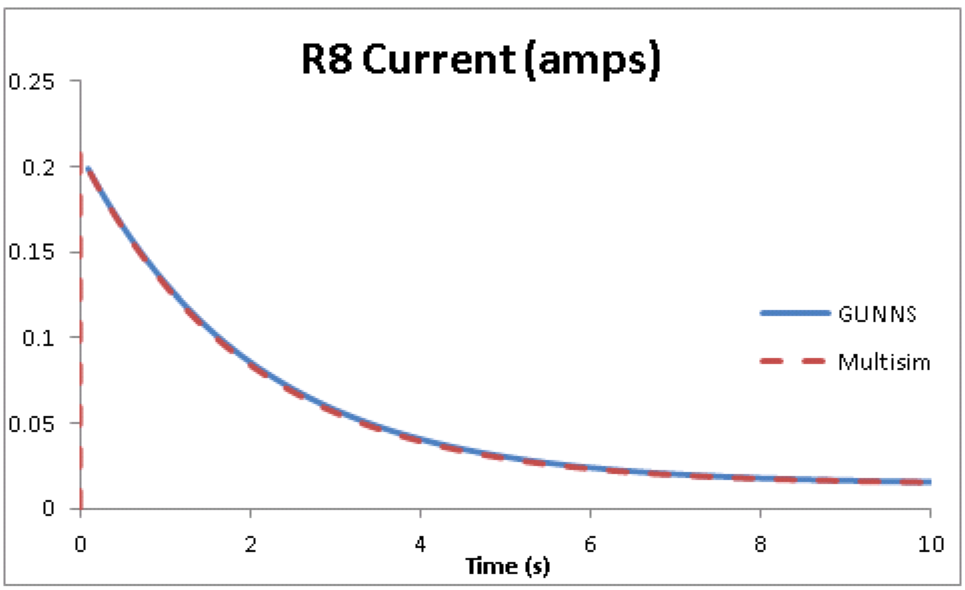

R2 Current (amps)
0.35
0.25
0.15
0.05
-0.05
-0.15
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

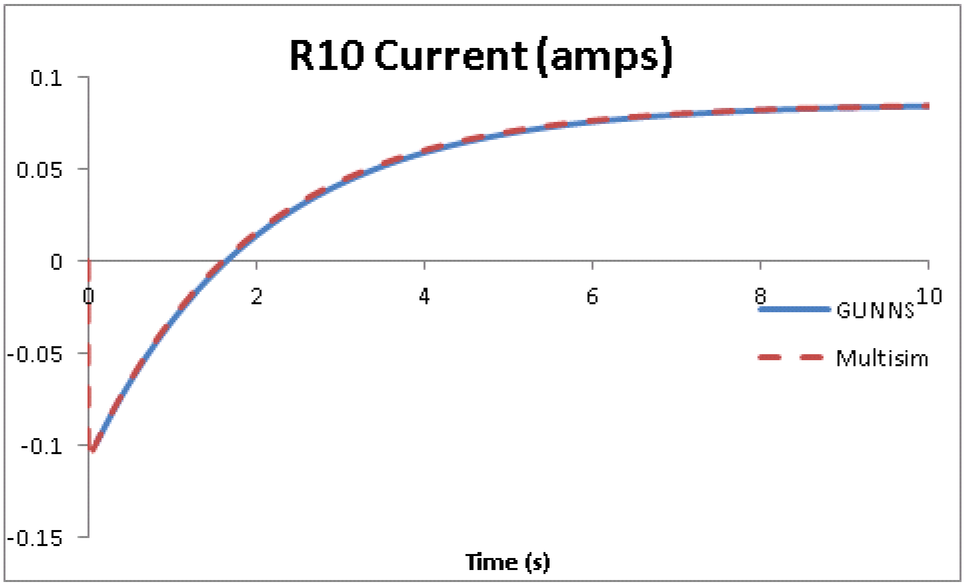

R3 Current (amps)
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

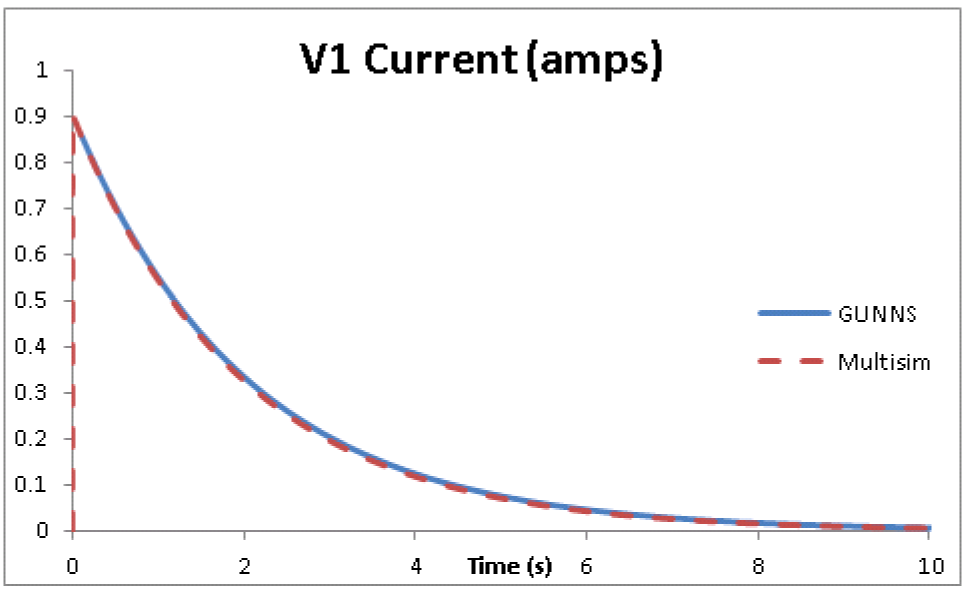

R5 Current (amps)
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
GUNNS
Multisim
Time (s)


R6 Current (amps)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
GUNNS
Multisim
Time (s)


R7 Current (amps)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

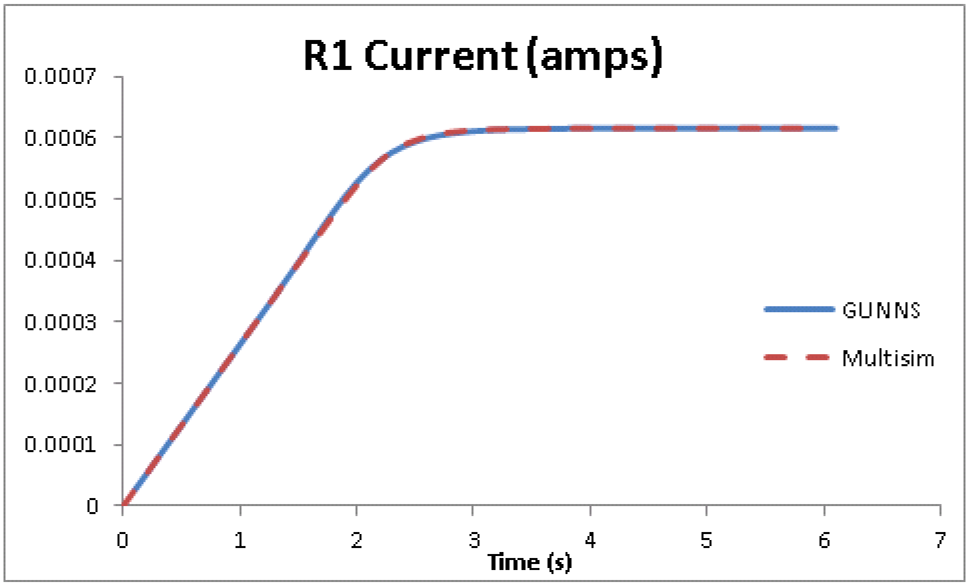

R8 Current (amps)
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
Time (s)
GUNNS
Multisim

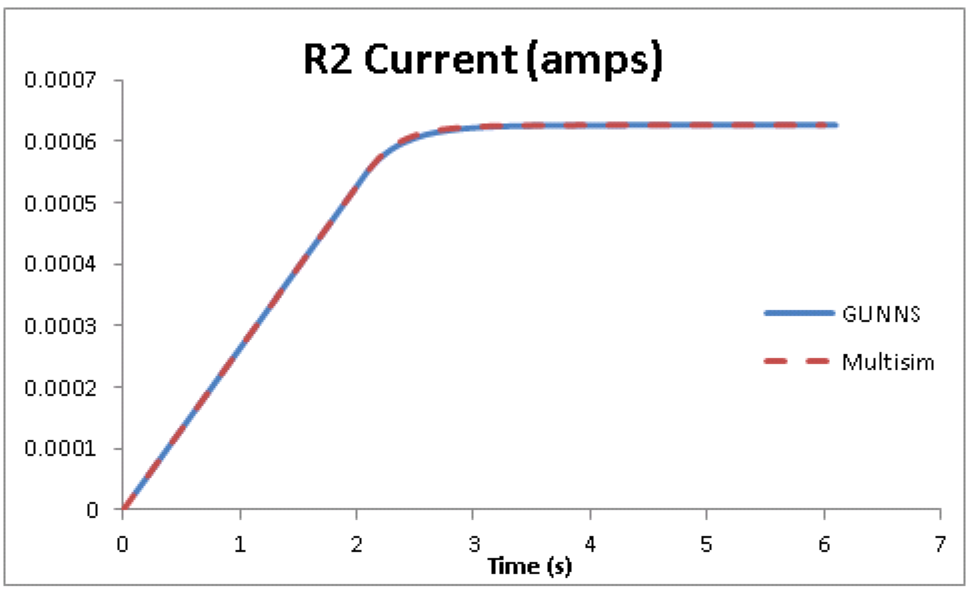




A.2 Test 5 Coplots

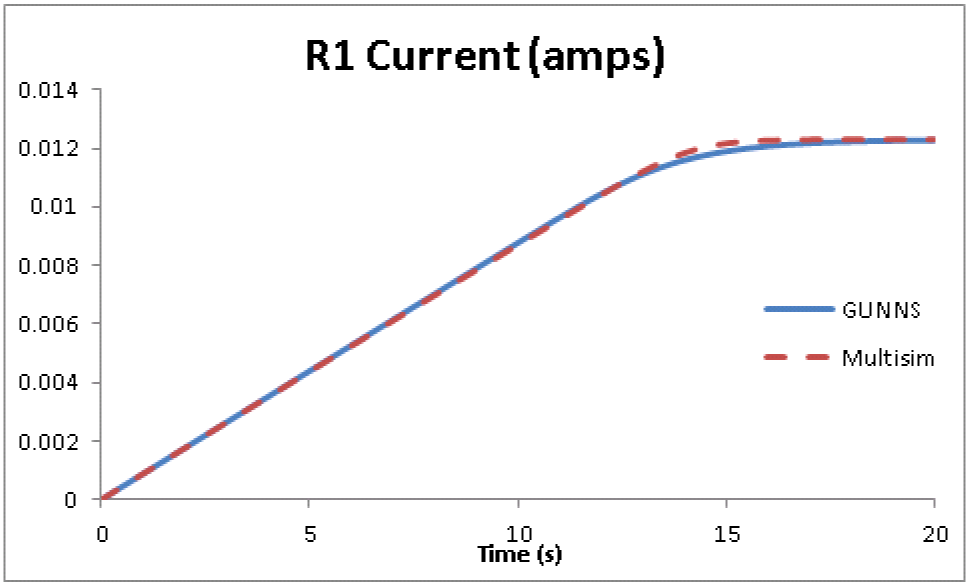
For reference, we present comparison plots between the model and software for Test 5 that were not used in Section 3.5:

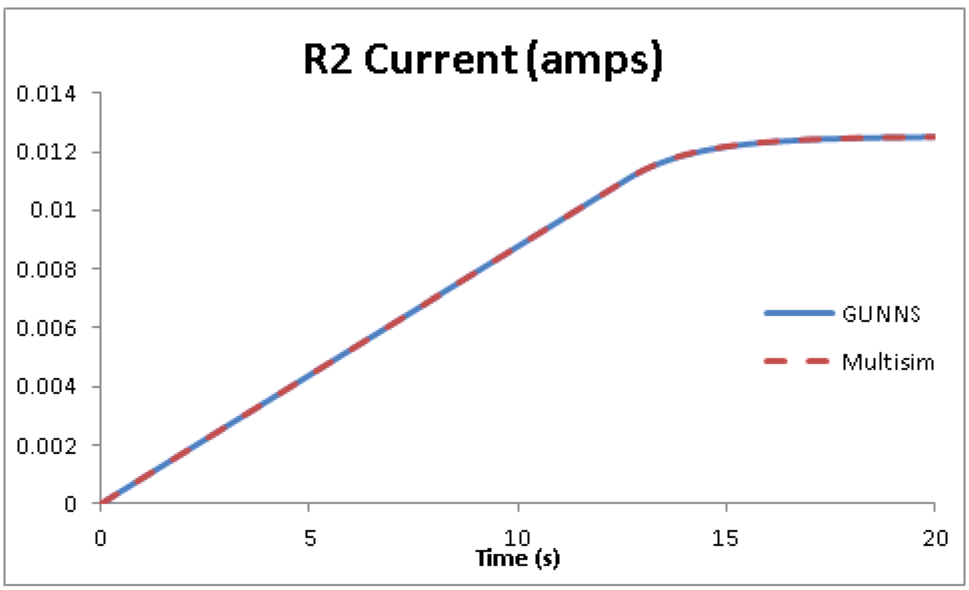




A.3 Test 6 Coplots

For reference, we present comparison plots between the model and software for Test 6 that were not used in Section 3.6:


R1 Current (amps)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15
20
Time (s)
GUNNS
Multisim


R2 Current (amps)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15
20
Time (s)
GUNNS
Multisim

References

[1] PV Cells Specifications, *New Models for Photovoltaic Cells in Multisim*, National Instruments, 2014, https://forums.ni.com/t5/National-Instruments-Circuit/New-Models-for-Photovoltaic-Cells-in-Multisim/ba-p/3473652.

[2] Solar Array Specifications, *PVEducation*, Christiana Honsberg and Stuart Bowden, http://pveducation.org/.

[3] Wikipedia contributors, *Diode," Wikipedia, The Free Encyclopedia*, https://en.wikipedia.org/w/index.php?title=Diode&oldid=792583585 (accessed July 31, 2017).