Simulating Distributed Battery and Solar Array Placement for Voltage Regulation

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SIMULATING DISTRIBUTED BATTERY AND SOLAR ARRAY
PLACEMENT FOR VOLTAGE REGULATION

By
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Bachelor of Science – Electrical Engineering
University of Nevada, Las Vegas
2013

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering—Electrical Engineering

Department of Electrical and Computer Engineering
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
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This thesis prepared by

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entitled

Simulating Distributed Battery and Solar Array Placement for Voltage Regulation

is approved in partial fulfillment of the requirements for the degree of

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Abstract

SIMULATING DISTRIBUTED BATTERY PLACEMENT FOR VOLTAGE REGULATION

(Michael Misch)

Abstract:

Energy storage has been around for many years in the US, mainly in the form of pumped hydro. However, in recent years, other storage technologies have developed quickly, with lithium ion batteries receiving significant investment and delivering technological and price improvements. Electricity storage has the potential to assist the US in transitioning to a smarter grid, as well as enabling increasing amounts of renewable generation to connect to the grid, without costly reinforcement works. Electricity storage can be co-located with power generation assets, installed along distribution systems for network services, or placed behind the meter, i.e., on the customer’s premises. This thesis focuses on the latter case.

Modern day electrical grids are complex and varied. Using a representative of a large number of grids we can simulate real world conditions and show how the system reacts to distributed solar arrays but can also show how the system can recover from voltage failures using residential sized distributed battery banks.

*It is hypothesized that through distributed use of battery systems that energy grids can facilitate a larger amount of renewable energy in regard to voltage and current limitations.*

The tasks to be performed include the following:

- Establish a base case network using the IEEE test feeder with local TMY data and local load data with Gridlab-D
• Establish a distributed and isolated number of solar arrays that real world outputs to cover how the grid would begin to fail relative to voltage and current limitations

• Study the ability of the grid to recover from voltage violations with the use of residential sized distributed battery systems using three utilization variations. Time of use shifting, peak shaving, and negative power shifting.

Based upon the found data we can discuss the added benefits of distributed battery systems and how they can be used to harden the grid against voltage failures.
Acknowledgements

I would like to thank first and foremost thank my advisor Dr. Baghzouz. Without his help and guidance none of this would be possible. My family and friends for their input and advice. My fiancé, Pratyusha Panchangam, for her support and patience. Finally, my management team Michael Gibo and Dale Crain who facilitated my ability to complete not just this project but attend all my classes for my masters.
Dedication

To Pratyusha Panchangam and keeping things honest.
Table of Contents

Approval page holder.................................................................................................................. ii
Abstract ........................................................................................................................................ iii
Acknowledgements.................................................................................................................... v
List of tables .................................................................................................................................. ix
Table of Figures ........................................................................................................................... x
Table of Equations ....................................................................................................................... xiii

Chapter 1: Introduction and motivation......................................................................................... 1
  1.1 Introduction .......................................................................................................................... 1
  1.2 Motivation ........................................................................................................................... 1
  1.3 Thesis Organization ............................................................................................................. 2

Chapter 2: Background & Economics ............................................................................................ 3
  2.1 Background ........................................................................................................................ 3
  2.2 Economics .......................................................................................................................... 4

Chapter 3: Overall Architecture & Design ..................................................................................... 8
  3.1.13 Node Test Feeder ......................................................................................................... 8
  3.2 Gridlab-D ........................................................................................................................... 9
  3.3 Battery ............................................................................................................................... 14
  3.4 Solar units .......................................................................................................................... 17
  3.5 Limitations ........................................................................................................................ 20

Chapter 4: Implementation ............................................................................................................. 22
  4.1 Base Case ........................................................................................................................... 22
  4.2 With Varying Load .............................................................................................................. 22
  4.3 With Solar .......................................................................................................................... 25
  4.4 Peak shaving....................................................................................................................... 28
  4.5 Negative load shifting ........................................................................................................ 30
  4.6 Time of use ......................................................................................................................... 33

Chapter 5: Results .......................................................................................................................... 35
  5.1 Peak shaving....................................................................................................................... 36
  5.2 Negative load shifting ........................................................................................................ 37
  5.3 Time of use ........................................................................................................................ 38

Chapter 6: Interpretation ................................................................................................................ 39
  6.1 Peak Shaving ..................................................................................................................... 39
6.2 Negative Load ......................................................................................................................... 40
6.3 Time of Use ............................................................................................................................. 41
Chapter 7: Conclusion .................................................................................................................. 44
Appendix A: Base Results ............................................................................................................. 47
Appendix B: With Feeder Load ..................................................................................................... 48
Appendix C: Auto-Regulator Enabled results .............................................................................. 51
Appendix D: Solar Results ............................................................................................................. 53
Appendix E: Peak Shaving Results .............................................................................................. 75
Appendix F: Negative Load Shifting Results ................................................................................ 93
Appendix G: Time of Use Results ............................................................................................... 111
Bibliography .................................................................................................................................... 129
Curriculum Vitae .......................................................................................................................... 131
List of tables

Table 1 Kerstig’s loads........................................................................................................................................23
Table 2 Ratios of loads to overall.......................................................................................................................23
Table 3 Solar simulation results ..........................................................................................................................26
Table 4 Peak shaving results ..............................................................................................................................36
Table 5 Negative load shifting results ................................................................................................................37
Table 6 Time of use results ..................................................................................................................................38
# Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>One-line diagram of system [2]</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Battery decision tree</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Single unit of solar</td>
<td>18</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Incorrect solar characterization</td>
<td>18</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Properly split solar characterization</td>
<td>19</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Peak shaving development</td>
<td>29</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Results of peak shaving</td>
<td>30</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Reverse power curve due to solar</td>
<td>31</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Negative power shift development</td>
<td>32</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Battery schedule</td>
<td>34</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Base result</td>
<td>47</td>
</tr>
<tr>
<td>Figure 12</td>
<td>System with varying load exterior nodes</td>
<td>48</td>
</tr>
<tr>
<td>Figure 13</td>
<td>System with varying load interior nodes</td>
<td>49</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Apparent power of system</td>
<td>50</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Real and imaginary power of system</td>
<td>50</td>
</tr>
<tr>
<td>Figure 16</td>
<td>System with auto-regulator exterior nodes</td>
<td>51</td>
</tr>
<tr>
<td>Figure 17</td>
<td>System with auto-regulator interior nodes</td>
<td>52</td>
</tr>
<tr>
<td>Figure 18</td>
<td>N611 solar results exterior nodes</td>
<td>53</td>
</tr>
<tr>
<td>Figure 19</td>
<td>N611 solar results interior nodes</td>
<td>54</td>
</tr>
<tr>
<td>Figure 20</td>
<td>N634 solar results exterior nodes</td>
<td>55</td>
</tr>
<tr>
<td>Figure 21</td>
<td>N634 solar results interior nodes</td>
<td>56</td>
</tr>
<tr>
<td>Figure 22</td>
<td>N645 solar results exterior nodes</td>
<td>57</td>
</tr>
<tr>
<td>Figure 23</td>
<td>N645 solar results interior nodes</td>
<td>58</td>
</tr>
<tr>
<td>Figure 24</td>
<td>N646 solar results exterior nodes</td>
<td>59</td>
</tr>
<tr>
<td>Figure 25</td>
<td>N646 solar results interior nodes</td>
<td>60</td>
</tr>
<tr>
<td>Figure 26</td>
<td>N652 solar results exterior nodes</td>
<td>61</td>
</tr>
<tr>
<td>Figure 27</td>
<td>N652 solar results interior results</td>
<td>62</td>
</tr>
<tr>
<td>Figure 28</td>
<td>N671 solar results exterior results</td>
<td>63</td>
</tr>
<tr>
<td>Figure 29</td>
<td>N671 solar results interior results</td>
<td>64</td>
</tr>
<tr>
<td>Figure 30</td>
<td>N675 solar results exterior nodes</td>
<td>65</td>
</tr>
<tr>
<td>Figure 31</td>
<td>N675 solar results interior results</td>
<td>66</td>
</tr>
</tbody>
</table>
Figure 65 N671 negative load shifting results interior nodes................................................................. 100
Figure 66 N675 negative load shifting results exterior nodes............................................................... 101
Figure 67 N675 negative load shifting results interior nodes............................................................... 102
Figure 68 N692 negative load shifting results exterior nodes............................................................... 103
Figure 69 N692 negative load shifting results interior nodes............................................................... 104
Figure 70 N6321 negative load shifting results exterior nodes.............................................................. 105
Figure 71 N6321 negative load shifting results interior nodes.............................................................. 106
Figure 72 N6711 negative load shifting results exterior nodes.............................................................. 107
Figure 73 N6711 negative load shifting results interior nodes.............................................................. 108
Figure 74 Distributed negative load shifting results exterior nodes ....................................................... 109
Figure 75 Distributed negative load shifting results interior nodes ....................................................... 110
Figure 76 N611 time of use results exterior nodes.................................................................................. 111
Figure 77 N611 time of use results interior nodes.................................................................................. 112
Figure 78 N645 time of use results exterior nodes.................................................................................. 113
Figure 79 N645 time of use results interior nodes.................................................................................. 114
Figure 80 N652 time of use results exterior nodes.................................................................................. 115
Figure 81 N652 time of use results interior nodes.................................................................................. 116
Figure 82 N671 time of use results exterior nodes.................................................................................. 117
Figure 83 N671 time of use results interior nodes.................................................................................. 118
Figure 84 N675 time of use results exterior nodes.................................................................................. 119
Figure 85 N675 time of use results interior nodes.................................................................................. 120
Figure 86 N692 time of use results exterior nodes.................................................................................. 121
Figure 87 N692 time of use results interior nodes.................................................................................. 122
Figure 88 N6321 time of use results exterior nodes.................................................................................. 123
Figure 89 N6321 time of use results interior nodes.................................................................................. 124
Figure 90 N6711 time of use results exterior nodes.................................................................................. 125
Figure 91 N6711 time of use results interior nodes.................................................................................. 126
Figure 92 Distributed time of use results exterior nodes.......................................................................... 127
Figure 93 Distributed time of use results interior nodes.......................................................................... 128
# Table of Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 1</td>
<td>Initial cost amount [19]</td>
<td>5</td>
</tr>
<tr>
<td>Equation 2</td>
<td>Interest rate calculation [19]</td>
<td>5</td>
</tr>
<tr>
<td>Equation 3</td>
<td>Net present value [19]</td>
<td>6</td>
</tr>
<tr>
<td>Equation 4</td>
<td>Tap position formula</td>
<td>9</td>
</tr>
<tr>
<td>Equation 5</td>
<td>Threshold formula</td>
<td>16</td>
</tr>
<tr>
<td>Equation 6</td>
<td>Battery efficiency formula</td>
<td>17</td>
</tr>
<tr>
<td>Equation 7</td>
<td>PF power relation formula</td>
<td>19</td>
</tr>
<tr>
<td>Equation 8</td>
<td>Per unit formula</td>
<td>20</td>
</tr>
<tr>
<td>Equation 9</td>
<td>Real power summation</td>
<td>24</td>
</tr>
<tr>
<td>Equation 10</td>
<td>Imaginary power summation</td>
<td>24</td>
</tr>
<tr>
<td>Equation 11</td>
<td>Apparent power of system</td>
<td>24</td>
</tr>
<tr>
<td>Equation 12</td>
<td>Available power to charge</td>
<td>32</td>
</tr>
<tr>
<td>Equation 13</td>
<td>Net demand</td>
<td>42</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction and motivation

1.1 Introduction

To say renewable energy has been on the rise in the last decade would be a vast under-statement. With the growing needs of the world coupled with that of the lowering cost of units themselves it is no wonder we can see a steep incline in the application of renewables. Between the years of 2009 and 2010 there were over 124,000 installations of solar equipment leading to a growth of 22% from the previous year [3]. This is not limited to the large-scale systems either. The growth of renewable energy on the user side has seen vast improvements over the years, in part, due to the idea of becoming more environmentally friendly. Unfortunately, this also leads to other issues. Our electrical grid was not made to be bidirectional, renewable sources as whole are exceedingly variable, and the market has no set standard for adoption yet. This plays havoc with the scheduling and regulation of our power from the distribution side.

1.2 Motivation

As renewable energy continues to be added into the grid the problems of penetration and voltage regulation will continue to grow. The rise of home based battery systems provides a unique opportunity for the green energy user in that they can now store and use their generated power on their schedule instead of being forced to sell it back to the company at a loss. This could lead to a variety of positive cash flow for the user with peak shaving and demand timing being integral. What we concern ourselves with here however is the opportunity to show that the implementation of these battery energy storage systems (BESS) could lead to countering the penetration of renewables as well as the
hardening of the overall systems to fluctuations. This work will show that when BESS is used in conjunction with solar the grid can experience an improvement in voltage regulation when used in a coordinated fashion.

1.3 Thesis Organization

This Thesis will go over the design considerations, testing, and results of our set up. Chapter 2 will cover our background in more depth as well as some economics of previous studies. Chapter 3 will discuss our distribution feeder as well as the coding language that was used and why for our implementation. Chapter 4 will introduce the system in more detail with instances of code being discussed to show what decisions were made. Chapter 5 will show our results and tables Chapter 6 will interpret these results and show how these might be expanded upon in the future for more advanced networks. Chapter 7 will conclude our thesis and bring more depth to the future work available for our project.
Chapter 2: Background & Economics

2.1 Background

The solar industry is growing rapidly [3]. Given the demand not only by the public but the private sector to meet future energy demands that are sustainable in nature means we must adapt and begin incorporating solar energy [4]. With the costs of systems continuing to fall and being predicted to fall [5], it only makes sense that this green alternative that can harness our natural world needs to be adopted.

For all the positives though renewables continue to cause havoc with our current grid due to their variability [6] [8] [9]. At times this could lead to the need to even introduce the new options in controlled manners [7]. Indeed, the greatest weakness of renewables is their inconsistency. These inconsistency’s manifest themselves in the system as rising currents and voltage imbalances that must be accounted for [11]. Thus, the importance to attempt to not only understand the limitations of the systems involved but additionally be able to counteract the effects. This is where battery energy storage systems (BESS) come in.

BESS are not a new technology but their ability to fill this gap in our grid is already being recognized as a need [12] [13] [14]. BESS have been used on large scale systems for years but as prices continue to fall and the technology continues to scale down we begin to see the rise of the residential customer looking to capitalize on their own ability to produce energy. In fact, this is how the systems are being advertised to the consumer with a focus on self-consumption to capitalize on your solar investment. Fronius states “A high proportion of self-consumption also ensures rapid payback of the cost of your photovoltaic system. Your aim must be to use as much of the solar power you generate as possible.” [16]. This however, does not mean that the consumers investment is not without mutual
benefit. Our infrastructure is generally slow to accept change and in some cases, will downright oppose it. Through our research we hope to show that not only can the customer benefit from the installation of a BESS in conjunction with their solar array but in fact that the grid can benefit as well.

2.2 Economics

I have separated out the economics from the main portion of the background as while it is a driving factor for our research it is ancillary to our main goals of showing what residential scale batteries can do for us on a grid wide scale.

As was discussed the growth of renewable energy is growing at a rapid rate and the adoption of the technology is at an unprecedented high when it comes to the public interest. Technologies have generally had a slow rate of inclusion when it comes to the public eye. Some of this is driven by ignorance and fear of the unknown while others simply don’t see the need to change over to a newer expensive system while the old system works well. Solar arrays however are being installed at an alarming rate such that our grid fears that it cannot keep up with the changes. Our battery systems are piggy backing off this renewable craze for the advantage to us all.

This is not an entirely new concept though. One paper shows that research was going on in Taiwan in 2001 [18]. This certainly isn’t the first paper of its kind being performed combining energy storage with that of solar arrays. In this paper they see the growth of renewables as a positive possibility for their grid and conduct experiments to see the practical applications of these systems and their viability for the market. It should be noted that this level of system is much larger than the residential systems we are looking at within our research.

Their research performs some tests under various charging and discharging plans and then simulated their results over months at a time to see how it would be affected by weather and changing
load demands. Using their results, they continued to research the costs and benefits as it applied to the new equipment and make mention that a major influence on the system could be the world market, but it is beyond their scope. Their findings were rather positive.

Assuming a well-placed site that would allow a great deal of solar energy to be captured they found that two of the three options they investigated would garner positive cash flow in time. Their plan A was around 14.3 years while their plan C was around 22 years.

They go on to discuss that some costs may be mitigated if you were to dual purpose the BESS so that it may act as a battery backup should power be lost from the grid. Their major costs had to do with the initial payments for the solar array systems and battery systems as well as the operational and maintenance costs. It is expected that the operational and maintenance costs will continue to rise as the facility would age.

This shows that even years ago batteries were already being studied as a possible add on to renewable energy and were indeed being found to be a viable option should the large-scale consumer choose to utilize them.

Moving on to more recent times another study was performed as recent as 2016 by some people at Arizona state university [19]. In this study they again look to attach a battery storage system with a solar array but are doing it on the residential scale and attempting to generate a net positive cash flow for the user before the failure of the units.

\[
\text{initial cost} = C_{PV} + C_{battery} + C_{electronics} + C_{installation}
\]

Equation 1 initial cost amount [19]

\[
\text{Real interest} = \frac{1 + \text{discount rate}}{1 + \text{inflation}} - 1
\]

Equation 2 interest rate calculation [19]
\[ NPV = \sum_{i=1}^{N} \frac{(E_i - O&M_i)}{(1 + R)^i} - \text{initial cost} \]

*Equation 3 Net present value [19]*

To find this out the above formulas were implemented. The initial cost is the calculation you would perform to find the cost of the system as a whole. The C in the system stands for cost. You may notice that the electronics are included in this formula which is often overlooked when deciding to purchase these systems. Batteries and solar panels may come bundled with the items, but it would still be desirable to consider purchasing the items separately as things become more integrated and there are more intelligent decisions being made for solar generation as well as battery charging it becomes more imperative that the electronics dictating these units be state of the art in order to maximize positive cash flow. The second equation is self-explanatory, but the third equation has to do with net present value. The NPV is a dollar value amount that attempts to simplify the complications of inflation, interest, degradation, maintenance costs, and the energy savings. In the formula E is for energy savings, O&M is for operational and maintenance costs, R is for the real interest rate previously found, and the initial cost is the same that was found previously as well. If you were to solve for I in the third equation when NPV=0 this would give you your payback period (PBP). This is the amount of time the unit would need to be operational for you to earn your initial investment back and begin experiencing a profit.

Using these formulas, they analyze their system under similar structures that we will in our research to see if a battery system is viable for the current residential customer. From their research it is easy to see their largest cost was the installation of the units. Of course, this makes sense. Earlier in their paper they discuss that only a very small percentage of people have batteries installed in their homes. With such a small pool of interested customers basic economics tells us that the costs for these services will be greater. With the more widespread adoption of the technology and availability these costs should fall over time.
Based upon their findings using peak shaving techniques, time of use techniques, and intelligent charging and discharging techniques they could find various PBPs related to their uses. In their conclusion they show that if any scheme like theirs was used and the system was purchased and installed within the next five years then you could not see any profit for at least ten years. This is shorter than the amount discussed in the 2001 Taiwan study, but it is hard to draw a parallel between the two of them since they are on completely different scales. Many times, costs can be amplified by the need for grid reliability or size relative to the homeowner who simply wants the units to be in place and run.

Ten years is an exceedingly long-term investment for a homeowner. Many systems will not even make the decade mark before needing to be fully replaced. Why does this matter to us? The solar industry is continuing to grow. Some power companies were offering cost breaks or even helping with the initial install costs to help accept the adoption of solar panels into the grid. Comparing this to battery units, if they were to begin getting government rebates or prorated rates in exchange for partial control of the units during times of great need you can cut down the PBP relative to the cost and rebate amounts.
Chapter 3: Overall Architecture & Design

3.1 13 Node Test Feeder

The IEEE 13 node test feeder is a widely known and heavily used distribution feeder in the power industry. The 13 nodes in the system may be a load, a connection point, or even a source. We have shown this below taken directly from Kerstig’s paper discussing his work with a distributed load on page 3[2]. In his work he chose this as his main test feeder for multiple reasons and we have gone with it for the same. Node 650 is our bus system and feeds directly into node 630 the regulator. From there the system goes into node 632 and on and on. We have kept Kerstig’s distributed loads between 632 and 671. Other noteworthy items in this system would be the transformer at point 634, the switch at point 692, and we also kept the system relatively loaded high. What we did remove however was the various shunts from the system. The reader may notice that there is a switch between nodes 671 and 692. This switch is a utility sized switched used to disconnect systems from the main grid as needed. For the duration of our studies we left the switch in the closed position. This was mainly due to the simulation solving method that was utilized. The forward backwards algorithm that was implemented is sensitive to islanding.

As our study is the ability to control the system’s voltage with minimal input from the generation side we wanted to focus on a more simplistic implementation. We did implement the automatic regulator but set the phase A and B at node 680 while phase C was kept at Kerstig’s original test point. Phase C showed the most sensitivity to the fluctuations of the system and at the furthest nodes, such as 611, it showed the most degradation. The regulator position is dictated in part by the below formula.
\[ A_R = 1 \pm 0.00625 \times \text{Tap} \]

*Equation 4 Tap position formula*

3.2 Gridlab-D

Gridlab-D was a coding language developed by Pacific Northwest Labs as a simple and free way for people to study power systems at various points. The language itself is based in C and shares many similarities to the parent language. Developed by a national laboratory the code runs with its own compiler and is relatively easy to adapt to. While the language itself is still under development there is a host of resources available online in their chatroom as well their online wiki. They provide a bare bones
version of the IEEE 13 node feeder and in the next section we will go over the finer points of the modifications that were performed. The code itself uses a backwards forwards method to analyze the system under test and can handle both balanced and imbalanced systems. Popular commands and their uses are summarized below.

While not a specific command in almost all the objects in the system you must specify which phases are being used. The obvious ones are A, B, and C. Gridlab-D also adds in a D phase but this is more of an additional note than an actual phase since it denotes that the phases are connected in the delta configuration. The N specification is for a systems neutral if it has one. There is also a split phase where you start getting into the basic 120v systems where you have a two hot and one neutral line connection possible.

The load commands. The load object is a unit that is plugged into the grid and can have a specified load amount by voltage, current, and various forms of power. For our purpose the data from the local test feeder was split up and individually read into the appropriate load thereby operating most of our loads in a scheduled manner. While generally loads draw energy from the system the load can also be a source of energy and was therefore used as our batteries.

The meter commands. The Gridlab-D meter replicates its namesake in the code and allows you to draw out system information such as measured power, current, and voltages. These must be placed with some thought as the system requires the meter to be placed in line if you would like to measure current.

The node commands. The node object forms a tie point where you can continue to make connections to other objects. While you can make connections without a node it is far easier to make multiple connections using this object. This could be classically compared to that of a bus system in the
academic sense. Multiple objects will branch away from this centralized node to our loads and other objects.

The player commands. While not an actual object within our test grid the player command was critical for the operation of all our system as it allowed us to model our batteries, real power, and reactive power. The player command reads in csv files and you can then use these values to schedule the system. This complicated things immensely for us as instead of being able to call in a complicated csv file with all loads already placed within it we were required to create individual files for the real and imaginary components for each unique load. This could have been simplified if the load was evenly distributed but since the feeder was imbalanced all the nodes had unique profiles.

The inverter commands. The inverter object is used in conjunction with our solar arrays to allow us to put power back into the system. The inverter will handle things such as power factor, efficiency, and connections back into the grid for the solar arrays. Inverter units in the grid today have many settings and abilities however our inverters will be limited to these options.

Line configuration commands. These commands are exceedingly important to us even if we do not modify them in any of our simulations. These commands are what actually sets the spacings between the different phases or even lists which phases are being carried by the cables.

The line commands. The line commands are configured using the line configuration settings. While their actual use is somewhat trivial we have to pay attention to them otherwise we can end up missing connections or rerouting power.

The solar commands. The solar array object is a bit unique compared to other programs and is specified by area instead of by its ability to produce. Attached to the inverter it will evenly distribute itself over the available phases. This is better discussed in the following section.
The battery command in Gridlab-D was not implemented. In the program there are two variations of the battery available. The first is the load following variation while the second is a scheduled version from an old version of Gridlab-D. While it may seem like an obvious solution to what we had wanted to accomplish there were several issues discovered during characterization.

In a load following configuration the battery must be placed in line with a given load and is given some limits for the unit the charge and some limits for the unit to discharge. The battery must be also parented to an inverter like that of the solar commands. These limits are critical for deciding how often and when the battery will activate but are not a direct way of scheduling the battery unless you intimately know how the load is going to behave. While we do have a great deal of knowledge for how we are going to change our schedule is on a completely different scale than the batteries we use. This will matter for us as if we use the batteries as we have used the solar arrays then we will have a battery on a multiplier scale and we will need to choose our limits relative to this. However, in practice the battery will then not act the same as hundreds of smaller ones. If we were to instead run tons of batteries on a smaller scale and set the limits we have another issue. If the limit said to charge when the load drops below 100kW and the current amount is 50kW the batteries immediately rail to the maximum that they can to try and counteract this. This does not act as a residential scale battery would. An attempt was made to use an out of line load to “schedule” the battery based on a fixed load we would schedule intelligently. This also doesn’t work as since the batteries are attempting to perform load following algorithms it senses that it could not make up the previously demanded power and each hour it has available, whether charging or discharging, it will attempt to “catch up” to the load it failed to make in the previous time. This leads to the battery to continuously rail again which is not how we would intelligently schedule a battery.
The scheduled variation was quite promising for our uses. You can specify the amount of energy in the battery and schedule it however you would want to. Similarly, to that of the solar command it forces you to evenly distribute the power over the available phases, so attention must be paid. Unlike the load following battery the scheduled battery command has no inverter to parent it to and is a self-reliant unit. The failing of this unit is that it can only be attached to units with three phases available which immediately removes multiple nodes from our test pool. This comes from the growth of Gridlab-D. Originally the team behind the code was planning on using the batteries as self-reliant units such as this but as the code evolved they realized the necessity to have the battery parented into an inverter to act as more of the decision-making portion of the unit. As such this variation of the battery was abandoned and works only as a legacy form of code while the other variation is still under development.

Given these shortcomings in the code it was decided to perform the battery calculations in excel and use a variation of the previously discussed load with a player to make a go between for our calculations and code interface. In most cases this was simplistic as creating a single csv file but on the distributed networks individual points again required that specialized files be made for each point.

The backward forward method is integral to our simulations as it is likely to produce the most realistic results. The method itself is exactly as the name sake. First the software will analyze the system in a given direction calculating the node voltages throughout the system. Then based on the findings of the algorithm it will use these node voltages to go back through the system and figure out how the system currents are performing, how the system is reacting to the power flow, and system losses. The algorithm will then hold this data off to the side and re analyze the system from the other direction recalculating from a current or power flow point of view and finding the node voltages from these values. Finally, after looking at the system from both directions the two solutions will be compared to one another to insure convergence. Should convergence not be found then the algorithm will again
analyze the system with the new parameters repeating the process until a solution can be found or the iteration limit is reached, and the system is considered unsolvable. For our simulations an iteration limit of 100000 was used. While this seems like a large number most often the code would complete its running and present a solution in under 10 seconds.

Gridlab-D also supports the Newton Raphson method of solving power flow systems. The reason that the forward backward method was implemented was due to the imbalanced nature of our distribution feeder. The method we used does not require a Jacobian matrix and as such allows the use of our system [17].

There is a weakness to our method in that it doesn’t handle islanding well. Islanding in our system would be the disconnection of a branch from the main grid. When doing this the solution would be unable to converge as at one point in time a switch, such as the one between 671 and 692, is closed allowing the grid to flow power into the branch but in the next it is opened so that there would be two power flows that would need to be monitored. One from the main branch where the bus system is in place and another from the isolated side of the distribution feeder where the power would be mainly from the solar arrays and the battery components. This became problematic for us as we had hoped to perform tests to investigate the usefulness of the batteries in a blackout condition or if there was a system failure that isolated a branch. As such using the backwards forwards method we will be unable to perform any simulations like this and had to abandon this aspect of our investigation.

3.3 Battery

The battery calculations were performed in excel. While Gridlab-D does have batteries within their language these were found insufficient for our needs. The battery logic tree is presented below. The battery characteristics are 12kWh capacity, 90% round trip efficiency, 10% depth of discharge hold
off, maximum charge capability of 1.6 kWh, and a maximum discharge capability of 5 kWh. We also have chosen to maintain a charging and discharging power factor of 1.

These settings were based on upcoming residential scale systems. The main limiting factor in this research was the maximum charge rate which related to the ability of the battery to offset the solar arrays. The second limiting factor was the capacity. When capacity is met but available energy remains more batteries must be installed. The discharge rate was far beyond our needs as in most cases the batteries discharged at a rate of 1 kWh. Otherwise the unit would become a source of problems instead of a helping hand.

While most residential customers in the world do not need to worry about the power factor of their systems this is not true for the industrial or commercial users. This is especially common in industrial settings as engines and heavy machinery are notorious for inducing power factor changes. When the power factor of a given system is too far out of spec, usually past .8 the supply side of the grid must inject large amounts of reactive power to counteract this and as such will begin charging much greater costs per kW to these customers. As such there was interest in using batteries to help correct the power factor of the user.
Using the above logic, it was placed inside of nested if statements within excel. N is the chosen number of batteries utilized, X is the chosen discharge rate, and the threshold from the first module was set at 0 for the negative load utilization or was calculated using the below formula for the peak-shaving implementation.

\[
\text{threshold} = \text{maximum}(P_{\text{solar}}) \times 0.6
\]

*Equation 5 Threshold formula*
Where P is for the real power component of our conglomerated solar unit and it is being multiplied by the 60% value to find the upper portion of it.

While we were applying the battery to our system through excel it is important to keep the formula below in mind for battery efficiency.

\[
\text{Energy efficiency} = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{V_D I_D \Delta T_D}{V_C I_C \Delta T_C}
\]

*Equation 6 Battery efficiency formula*

Where the D subscript denotes discharging and the C subscript denotes the charging.

3.4 Solar units

For our grid level development of solar we will be distributing it in blocks. After characterizing the outputs of the solar unit in Gridlab-D we then set 325 square feet as the amount for a block. Shown below is the output of the block at a solar efficiency of 15%, a power factor of .8, and an inverter efficient of 90%. This graph is showing the real component only. Since we are using a power factor of .8 there will still be a nonreal component being placed into the system. This number had to be maintained in multiples of 325 square feet if there were multiple phases available. If there was a single phase the multiplier was 325. If there were two phases available, the multiplier was 650. If there were three phases available, the multiplier as 975. This was to insure an even distribution of our solar arrays as whole blocks over our available phases.
The above shows us the single solar unit but below will show why it is important to pay attention to how it is being applied in the system.
Figure 5 Properly split solar characterization

As you can see Gridlab-D will take the available power and evenly split it over the available phases. You may notice that the power of the system is larger than our officially used version. That is because this was when the unit was used at 20% efficiency instead of at 15% where we ended up. The original amount was deemed too strong compare to the average solar installation. You may also notice that the power is positive when we should expect that it is negative. When finding the apparent power of the system you lose the sign convention but the data is still the same.

The power factor is an important component to this as well and Gridlab-D will be using our input using the following formula. Some of the more modern-day inverters available to the solar owner can choose the power factor that is used. We kept ours fixed for all our simulations.

$$P_F = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}$$

*Equation 7 PF power relation formula*

Where P is the real component, S is the apparent power, and Q in the nonreal component.
3.5 Limitations

For our simulations we focused on two limitations. The current carrying capacity of our lines and the voltage per unit measured throughout the system. While the voltage spikes can be somewhat subjective to duration and use [10] thermal considerations for current cannot be ignored or negotiated against.

The voltage limitations we are nominally going for is between .95 and 1.05 per unit. This was calculated using the formula from below.

\[ V_{pu} = \frac{V}{V_{base}} \]

*Equation 8 Per unit formula*

The per unit system is used in the power industry as a simpler way of calculating what is occurring in the grid. When you have to constantly switch to either side of a switch or transformer the use of the per unit system allows you to make comparisons without having to keep the specifics at hand.

Where \( V \) is the voltage of the system. The base voltage in most cases was a nominal 2400V while the voltage on the other side of the transformer was a nominal 480V. The result of a system that is over voltage could lead to failure or destruction of connected materials and is regulated to be within spec by the power industry. Likewise, the result of a system that is under voltage could mean the intermittency of the connected materials. The grid itself could receive damage from these fluctuations. While the U.S grid is highly reliable it is not unheard of in other parts of the world that surge protectors are the norm instead of the exception due to the unreliability of the grid.

The current limitations are more unforgiving. As a line carries more current it will continuously heat up and if too much is expected of it the line will fail and begin to consume itself. Where applicable the lines have current limitations based upon real configurations. These configurations are based upon
industry standards. As the violation of these limits would be catastrophic when then they occur we have chosen to remove any occurrences of them from our available simulations. While batteries may be able to help the system recover from these occurrences we do not want to rely on them to be available.
Chapter 4: Implementation

4.1 Base Case

To set a basis of what was studied the Gridlab-D version of the feeder was simulated and studied. Using the results, it was possible to show an approximate input load. The load specified in the simulation was only barely able to maintain .95 voltage P.U. without the help of capacitor shunts. Based upon this fact the load that was implemented was pared down to be of similar scale to the base case. As those that created this line left in capacitive shunts, and some current loads instead of the more common power demand loads, the results are not the most representative of our system, but it does give us a starting point before these items were removed. The resulting outputs were graphed and placed within the appendices.

4.2 With Varying Load

This load was based upon a reading from a local neighborhood distribution feeder. The load was far too large for our given system as it comes from that of a much larger system but does incorporate the unique demands of air conditioners running in the desert during the summer. It was roughly pared down by a quarter and then distributed, by percentage, from the original load profile to the individual loads of the system. From this data the system was studied and was then re-simulated using the regulator with automated settings. Under these settings the system maintains the voltage between .95 and 1.05 volts per unit which is ideal for wide power distribution.
<table>
<thead>
<tr>
<th>Node loads in KW and KVAR</th>
<th>Real A</th>
<th>Imag A</th>
<th>Real B</th>
<th>Imag B</th>
<th>Real C</th>
<th>Imag C</th>
</tr>
</thead>
<tbody>
<tr>
<td>634</td>
<td>160</td>
<td>110</td>
<td>120</td>
<td>90</td>
<td>120</td>
<td>90</td>
</tr>
<tr>
<td>645</td>
<td>0</td>
<td>0</td>
<td>170</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>646</td>
<td>0</td>
<td>0</td>
<td>230</td>
<td>132</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>128</td>
<td>86</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>671</td>
<td>385</td>
<td>220</td>
<td>385</td>
<td>220</td>
<td>385</td>
<td>220</td>
</tr>
<tr>
<td>675</td>
<td>485</td>
<td>190</td>
<td>68</td>
<td>60</td>
<td>290</td>
<td>212</td>
</tr>
<tr>
<td>692</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>170</td>
<td>151</td>
</tr>
<tr>
<td>611</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>170</td>
<td>80</td>
</tr>
<tr>
<td>6711</td>
<td>5.666</td>
<td>3.333</td>
<td>22</td>
<td>12.666</td>
<td>39</td>
<td>22.666</td>
</tr>
<tr>
<td>6321</td>
<td>11.333</td>
<td>6.666</td>
<td>44</td>
<td>25.333</td>
<td>78</td>
<td>45.333</td>
</tr>
</tbody>
</table>

**Table 1 Kerstig’s loads**

<table>
<thead>
<tr>
<th></th>
<th>Real A</th>
<th>Imag A</th>
<th>Real B</th>
<th>Imag B</th>
<th>Real C</th>
<th>Imag C</th>
</tr>
</thead>
<tbody>
<tr>
<td>634</td>
<td>3.46%</td>
<td>3.29%</td>
<td>3.46%</td>
<td>4.28%</td>
<td>3.46%</td>
<td>4.28%</td>
</tr>
<tr>
<td>645</td>
<td>-</td>
<td>-</td>
<td>4.90%</td>
<td>5.95%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>646</td>
<td>-</td>
<td>-</td>
<td>6.64%</td>
<td>6.28%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>652</td>
<td>3.69%</td>
<td>4.09%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>671</td>
<td>11.11%</td>
<td>10.47%</td>
<td>11.11%</td>
<td>10.47%</td>
<td>11.11%</td>
<td>10.47%</td>
</tr>
<tr>
<td>675</td>
<td>14%</td>
<td>9.04%</td>
<td>1.96%</td>
<td>2.85%</td>
<td>8.37%</td>
<td>10.09%</td>
</tr>
<tr>
<td>692</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.9%</td>
<td>7.18%</td>
</tr>
<tr>
<td>611</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.9%</td>
<td>3.81%</td>
</tr>
<tr>
<td>6711</td>
<td>.1635%</td>
<td>.1586%</td>
<td>.6347%</td>
<td>.6026%</td>
<td>1.13%</td>
<td>1.08%</td>
</tr>
<tr>
<td>6321</td>
<td>.3270%</td>
<td>.3171%</td>
<td>1.27%</td>
<td>1.21%</td>
<td>2.25%</td>
<td>2.17%</td>
</tr>
</tbody>
</table>

**Table 2 Ratios of loads to overall**

These percentages were calculated by summing up of the imaginary and real components of the system and then performing calculations to determine the percentage that
the load corresponds to the overall. This allowed for some simplification during processing as a few loads are equivalent to one another and therefore did not need their own csv files created for them.

The above percentages will not sum up to 100. This is because during testing and simulation it was found that the load for 634 phase A was too high. This was leading to currents that were above the maximum allowed in the line and in a real-life situation would have led to the eventual failure of the line. As such the real component was reduced to 75% of its initial value and the imaginary component was reduced to 63% of its initial value.

The system itself was checked against the load given by using the following formulas after reading out the values and placing the csv files into excel.

\[
P_{\text{system}} = \sum_{k}^{n} P_{\text{nodes}} (k, n)
\]

*Equation 9 Real power summation*

\[
Q_{\text{system}} = \sum_{k}^{n} Q_{\text{nodes}} (k, n)
\]

*Equation 10 Imaginary power summation*

\[
S_{\text{system}} = \sqrt{P_{\text{system}}^2 + Q_{\text{system}}^2}
\]

*Equation 11 Apparent power of system*

Where P is the real power, Q is the imaginary power, and S is the apparent power of the system.

These values were then graphed and placed in the appendices. The values were found to be within acceptable expectations with the added changes the system placed upon it.
4.3 With Solar

By going load by load the system was characterized by solar PV penetration. Using a base amount of solar it was multiplied until failures started to occur within the system. These failures were defined by violating the 1.05 or .95 volts per unit. In some rare cases it was possible to raise or lower the regulators voltage settings to allow more PV into the system. This is applicable to real life systems as the distribution side of the system would vary their settings to maintain distribution. These values were implemented using local Las Vegas TMY data and was characterized prior to implementation.

The following table is laid out, so the columns are the test being performed and the rows are the readings and values used for the test. As an example, column 1 is the “bare” test which corresponds to when nothing was added to the system. Row 1 corresponding to that column shows that when under the bare condition test node 611 maximum current was read as 78A.
<table>
<thead>
<tr>
<th></th>
<th>Bare</th>
<th>611</th>
<th>634</th>
<th>645</th>
<th>646</th>
<th>652</th>
<th>671</th>
<th>675</th>
<th>692</th>
<th>6321</th>
<th>6711</th>
<th>distributed</th>
<th>Rating</th>
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</thead>
<tbody>
<tr>
<td>611</td>
<td>78</td>
<td>125</td>
<td>79</td>
<td>78</td>
<td>79</td>
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<td>78</td>
<td>78</td>
<td>78</td>
<td>78</td>
<td>230</td>
</tr>
<tr>
<td>Max Current</td>
<td>633</td>
<td>57</td>
<td>57</td>
<td>309</td>
<td>57</td>
<td>57</td>
<td>57</td>
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<td>76</td>
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<td>497</td>
<td>497</td>
<td>500</td>
<td>497</td>
<td>497</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>646</td>
<td>59</td>
<td>59</td>
<td>59</td>
<td>245</td>
<td>59</td>
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<td>59</td>
<td>59</td>
<td>230</td>
</tr>
<tr>
<td>Max Current</td>
<td>652</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>144</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>61</td>
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<td>310</td>
</tr>
<tr>
<td></td>
<td>675</td>
<td>220</td>
<td>222</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>219</td>
<td>329</td>
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<tr>
<td>Max Current</td>
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<td>259</td>
<td>257</td>
<td>258</td>
<td>257</td>
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<td>256</td>
<td>257</td>
<td>256</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Solar area</td>
<td>_</td>
<td>26000</td>
<td>Current failure</td>
<td>58500</td>
<td>Current failure</td>
<td>29250</td>
<td>0</td>
<td>48750</td>
<td>105300</td>
<td>48750</td>
<td>195000</td>
<td>107250</td>
<td>varies</td>
</tr>
<tr>
<td>Number of units per phase</td>
<td>_</td>
<td>80</td>
<td>Current failure</td>
<td>90</td>
<td>Current failure</td>
<td>90</td>
<td>50</td>
<td>108</td>
<td>50</td>
<td>200</td>
<td>110</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Overall peak penetration</td>
<td>_</td>
<td>7.77%</td>
<td>_</td>
<td>8.75%</td>
<td>_</td>
<td>8.75%</td>
<td>4.86%</td>
<td>10.5%</td>
<td>4.86%</td>
<td>19.4%</td>
<td>10.69%</td>
<td>_</td>
<td>-</td>
</tr>
<tr>
<td>Load specific peak penetration per phase</td>
<td>_</td>
<td>C 158%</td>
<td>_</td>
<td>B 175%</td>
<td>_</td>
<td>A 237%</td>
<td>44%</td>
<td>A 75%</td>
<td>B 535%</td>
<td>C 125%</td>
<td>C 99.2%</td>
<td>A 59.4%</td>
<td>B 15.3%</td>
</tr>
</tbody>
</table>
Of note within this table are the nodes 634 and 646. You can see on both that when simulated there are current failures in the lines. Node 634 is on the other side of the transformer and previously we discussed this line being reduced to conform within its limits. Since this is a transformer however when the solar is at the maximum for the day it is overpowering the load and node 634 becomes a source of energy. With the unit attempting distribute power back into the grid it must pass through the transformer to achieve this. The primary side of the unit is at 4160 V and the secondary is at 480. This step-down transformer then becomes a step-up transformer from the opposite direction leading to massive currents that far exceed limitations. Node 646 has a load on phase B like that of its parent 645. Also like that of its parent it carries and unused phase C. As we are utilizing all connections possible for both batteries and solar arrays we have added units to both phases. This leads to an immediate reverse current whenever the solar arrays are outputting. Node 645 experiences the same issues but as it is closer to the core of the distribution feeder these fluctuations in voltage are better regulated.

Since these currents would lead to catastrophic failures these two nodes will be removed from the remainder of the tests as even though the battery systems could help to recover from these infractions it should not be relied upon.

You may also notice that the switch portion of the grid does not have a current rating. There is no available material covering what the switch is capable of, but we can assume that it has a high current rating given that it is in the grid as a disconnection point and were it to activate while under power it would experience a high amount of current when the disconnection occurs.
Because minor violations in voltage are allowed on small scales [10] it is a relative determination to choose when enough solar has been added. I have specifically aimed to have a violation that goes above the 1.05 threshold on a consistent basis.

4.4 Peak shaving

As we discussed, renewable energy can have wide variations. Solar output is entirely dependent on the skies above it and even a low amount of cloud cover can drastically alter the maximum wattage that is experienced. Las Vegas is one of the prime locations in the world when it comes to solar but even then, we are still subject to the weather. Coupling this with the variability of daily use within a household there will be times where the overall load can fluctuate rapidly during the day. Using a peak shaving technique, we will store the energy above a certain threshold and then output that energy later. This has benefits for both the user as well as the provider.

The provider will get the benefit from not having severe spikes of solar energy invading the grid as well as the consistency of a battery discharging at a time when there is more peak demand. The user will be able to utilize their energy during their own high use period as well as even when a grid will allow the user to push their excess energy back into the system their credit will be lower than the cost of simply purchasing it. As such this implementation can be seen as controlled by either party as both may choose to perform it.
Figure 6 Peak shaving development

Shown above is an example of the building of our battery load over a few early days. The blue is our solar load and it may seem small but that is because we have already focused in on the portions we want to capture for later output. You can also see that we have chosen to output when we are not reading any solar in. This will prevent the battery systems from creating spikes in the system stronger than the ones we are trying to eliminate in the first place. Shown below is the resulting power measurements with both solar and battery load active. You can clearly see the peaks removed from the solar and the small squares when the battery systems kick in.
Batteries were continuously added to the system until the peaks of all were accounted for. In many cases this could be single units. It is important to remember that we are charging the batteries evenly so the inclusion of a single battery for a small amount of uncaptured energy is not cost effective to our overall system but is necessary for the sake of the simulation at large.

4.5 Negative load shifting

As the solar arrays being to reach their maximum output the system could begin to experience power reversal. During these times the solar arrays become a source of energy for the grid but one it wasn’t designed for. These fluctuations can be very large and very sudden especially under the conditions we are testing the grid. Shown below we have the load curve from 652 as it has more and more solar placed upon it. The amount of solar was taken from the solar experiments to see the P.V.
penetration of the node. 652 was chosen as our testing point for many of our small-scale simulations as it is a single phase and the connection is a direct and simple one. Distribution lines 6321 and 6711 are distributed loads and were made to simulation the effects of a distributed load along the feeder. This complicated the diagnostics along those nodes as we can see power flowing to and from the units from the high points as well as the low. This leads us to using 652.

**Figure 8 Reverse power curve due to solar**

When there is no solar on the system there are minor fluctuations from day to day use in yellow. During the day on grey we can see that even a small amount of solar can be enough to overcome the demand and begin power generation back into the grid. We continue to show the buildup of energy at both half and full capacity. These can also be thought of in the capacity that they are lightening our load and causing the voltage per unit to float up until the regulator is unable to maintain the specified requirement.
Capturing this power before it gets back into the grid will benefit both user and provider. As previously discussed if the user does not get credit or gets less credit than the cost of purchasing power then storing the energy and releasing it when their demand is highest is key. Again, similar to peak-shaving, storing the energy and releasing it into the grid when demand is highest also means the overall energy demand becomes more manageable.

![Negative power shift development](image)

*Figure 9 Negative power shift development*

Shown above we can see again both solar power and battery power over time. The solar power is much larger than the peak-shaving implementation this is because instead of simply charging the top 60% of the curve we are utilizing the curve whenever it is greater than the demand curve. Batteries were continuously added until the amount of negative power over our simulation time was completely accounted for. Again due to the nature of evenly charging our system this could lead to the introduction of a single battery for a small amount of uncaptured energy.

\[
P_{\text{charge}} = P_{\text{load}} - P_{\text{solar}}
\]

*Equation 12 Available power to charge*

The above simple equation is how the available power for the battery was found. \( P \) is the real power component. Again, this is on a node by node basis and as such will vary greatly depending on how
much power was delegated to each node. As was discussed during the solar simulation development
some nodes exhibit the unusual condition where a load was placed upon a phase while the other phase
remained open. These simulations will require more batteries since immediately all the power the solar
arrays output will become negative. It does allow us to see the effects of batteries on the systems with
only solar on these phases.

4.6 Time of use

Time of use is based upon the principle that the average home owner will use most of their
energy between the hours of 1 p.m. and 8 p.m.. Solar arrays however will begin outputting early in the
morning around 6 a.m. and continue to output until the sunset around 6 p.m.. Using our battery, we can
take the energy that is output and distribute it during the peak hours. This can be highly advantageous
for us as in many parts of the world it is beginning to become the norm to charge higher prices as it is
more difficult for utilities to handle this increased load.

This leads us to need to discharge the battery over a 7-hour period in the afternoon. To help
alleviate the solar impact to the grid we have chosen to charge the batteries in the prior 7-hours before
discharging.

This becomes important to customers who are attached to grids that enforce peak power costs.
While the costs per kW are usually only small these charges are amplified by the fact that you are
consuming the majority of your energy during these times. The utilization of batteries to limit your grid
power draw during these times is a major contributor to what is making batteries more viable
economically.
Shown above is a single battery unit charging and discharging over a few days. The discharge rate was set at 1542.847 W per hour for the and the charge rate was 1541.7 W per hour. The numbers in the graph are slightly lower and higher due to the losses incurred while charging and discharging. This means the battery evenly charges and discharges over the 14-hour period.
Chapter 5: Results

Due to the size and complexity of the system and diagnostics the graphs were placed in the appendices and the results summarized in tables. These results in the appendices were limited to the traces that were found to be out of bounds during tests and those that resulted from the changes within the system. This was done to limit the reporting of useless data and help the reader focus in on the changes that were produced by our tests.
5.1 Peak shaving

<table>
<thead>
<tr>
<th></th>
<th>611</th>
<th>645</th>
<th>652</th>
<th>671</th>
<th>675</th>
<th>692</th>
<th>6321</th>
<th>6711</th>
<th>distributed</th>
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<tbody>
<tr>
<td>Improved node current</td>
<td>28</td>
<td>16</td>
<td>33</td>
<td>-</td>
<td>20</td>
<td>-</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>48750</td>
<td>105300</td>
<td>48750</td>
<td>195000</td>
<td>107250</td>
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<td>108</td>
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<td>200</td>
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<tr>
<td></td>
<td>692 C</td>
<td>645 B</td>
<td>692 A</td>
<td>675 B</td>
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<td>675 B</td>
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<tr>
<td># of Batteries</td>
<td>73</td>
<td>83</td>
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<td>-</td>
<td>680 A</td>
<td>680 B</td>
<td>675 A</td>
<td>680 B</td>
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<tr>
<td>Notes</td>
<td>Improve ment on all account s and while 684 C is still out of spec it is improve d</td>
<td>Improve ment on all account s</td>
<td>Magnitu de of violatio ns decreas ed</td>
<td>Magnitu de of violatio ns decreas ed</td>
<td>Magnitud e of violations decrease d</td>
<td>Magnitud e of violations decreas ed</td>
<td>Improve ment on all accounts. Small infractio ns that are discount ed</td>
<td>Improve ment on all accounts. Small infractio ns that are discount ed</td>
<td>Magnitud e of violations decreased</td>
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Table 4 Peak shaving results
## 5.2 Negative load shifting

<table>
<thead>
<tr>
<th>Improved node current differential</th>
<th>611</th>
<th>645</th>
<th>652</th>
<th>671</th>
<th>675</th>
<th>692</th>
<th>6321</th>
<th>6711</th>
<th>distributed</th>
</tr>
</thead>
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<tr>
<td></td>
<td>34</td>
<td>19</td>
<td>-80</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Number of units per phase | 80  | 90  | 90  | 50  | 108 | 50  | 200   | 110   | 15          |

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of Batteries</td>
<td>209</td>
<td>241 B</td>
<td>296</td>
<td>54 B</td>
<td>228 A</td>
<td>146 A</td>
<td>650 A</td>
<td>358 A</td>
<td>348 B</td>
<td>343 C</td>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
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|-----------------|-------|-------|-------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|

<table>
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<tr>
<th>Notes</th>
<th>Recovered on all accounts but forced violations of .95. Can be fixed with regulator</th>
<th>System nominal</th>
<th>System nominal</th>
<th>Lowered the magnitude of violations</th>
<th>Lowered some violations while magnifying others as well as forcing more out of spec</th>
<th>Lowered the magnitude of violations</th>
<th>Lowered some violations while magnifying others as well as forcing more out of spec</th>
<th>Lowered the magnitude of violations</th>
<th>Lowered some violations while magnifying others as well as forcing more out of spec</th>
<th>Lowered the magnitude of violations</th>
</tr>
</thead>
</table>

*Table 5 Negative load shifting results*
### 5.3 Time of use

<table>
<thead>
<tr>
<th>Improved node current differential</th>
<th>611</th>
<th>645</th>
<th>652</th>
<th>671</th>
<th>675</th>
<th>692</th>
<th>6321</th>
<th>6711</th>
<th>distributed</th>
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</thead>
<tbody>
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<td></td>
<td>-13</td>
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<td>-</td>
<td>13</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Number of solar per phase          | 80  | 90  | 90  | 50  | 108 | 50  | 200  | 110  | 15          |

|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|

| # of Batteries                     | 50   | 50   | 50   | 75   | 75   | 100  | 100  | 75   | 15  |

|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|

| Notes                              | Improves the severity and frequency. Induces .95 violation on 675 A | Improves 646 B but forces 646 B higher | Improves both but they remain out of spec | Generally, no change | Generally smoothing but remains out of spec | Generally smoothing but remains out of spec | Generally smoothing but remains out of spec | General smoothing but remains out of spec |

*Table 6 Time of use results*
The majority of nodes experienced an improvement at the nodes under test although some experienced the opposite.

Chapter 6: Interpretation

Outside of the individual results we should also consider the usage of the batteries themselves. As with all things batteries degrade over time. In almost all simulations, on all days we are charging and discharging our batteries to some capacity. This could lead to degradation of the battery over time relative to its state of charge [1]. This was not a consideration in this project.

Additionally, as previously mentioned, while we have made sure to stay within thermal restrictions regarding current limitations these were not the main component observed in this project. It should be noted however that in many cases the maximum current that was observed with batteries installed decreased.

6.1 Peak Shaving

Using our peak-shaving technique we can see a large improvement in all cases and the system fully recovers in 3 cases (645, 6321, and 6711). We can note that those that remain out of specification have improved. It is important to note that using this method we are still allowing 60% of the solar energy to tap into the grid. Days that are unseasonably cold would lead to lower demand from the grid, but the skies could remain clear and solar will still output at peak demand leaving a larger impact.

Based upon our results we could add more solar in the cases of 645, 6321, and 6711. These locations all happen to be closer to the grid center where the regulator would have the most influence over the results. As we move further out from the center previous nodes would need to fluctuate with more magnitude to support the changes at the far ends.
We can also note that in all cases we used less battery systems than we had solar units installed. This is important as we want these simulations to provide benefit to both the consumer as well as the provider. It shows that we have a ratio of around .9 battery ownership to solar ownership.

Going into the test 24 phases were out of spec and based on our results we were able to lower the number of phases down to 14. This leads to a cumulative improvement of about 41%. The remaining nodes again still showed an improvement. Based on phases improved this was the most effective method.

6.2 Negative Load

Like that of the peak-shaving method we show promising results with all tests showing an improvement in violations and a few showing that we have helped the system to recover successfully. In basic terms this makes sense since the negative load utilization shares many traits with the last methodology only on a much larger scale.

However, these results do show a much larger amount of batteries used. In many cases we needed triple the amount of batteries as we did solar units. Some nodes show a difference of batteries used on each phase. Since the loads are phase dependent and we evenly distributed the solar over that of the connections at each node it is expected that those with larger loads will need less batteries and vice versa for the lighter loaded phases. Some nodes in fact have no load upon them at all as was discussed previously so when performing the mathematics to isolate the amount of negative energy we are in fact calculating the amount of batteries it would take to fully absorb the solar power that is generated.

In some instances, we observed that while we have generally smoothed out the curves of the feeder we have introduced additional instances of failure. Again, this can be expected with how we are
implementing the batteries (as synchronized units that act in concert) we are at times performing similar issues as the solar has only later in the day. At most times this isn’t an issue as the day proceeds the demand of the feeder naturally increases however on days where the load may not be as large it cannot combat the combined power of the batteries outputting.

Remember in these two cases we have chosen to only output the batteries when the solar is completely shut off. However, that does not mean we are not overpowering the nodes still. In both situations we have chosen to output 1.2kW an hour. In the case of node 675 we have had to utilized over 300 batteries on phase B. That means that when the batteries begin outputting they are pushing 360kW into the system on startup and will continue to do so until depletion. To put that into perspective that same node only required 108 units of solar to force it out of specification. This means that the batteries could easily outdo even what the solar component could perform given the right conditions.

Going into the test we had 24 phases that were out of spec and of those it improved 6. This leads to an improvement of about 25%. Since it does force some phases out of specification though it could be seen to be less effective. Instead of 24 there are now 30 including the new ones. Again, some of these new ones can be fixed with voltage regulation shifting.

6.3 Time of Use

Of the three variations that were attempted time of use was the least successful but was still able to garner positive results. I have annotated the results as that the results are generally smoother. The very predictable very stable battery is taking the variable solar energy and reducing it in the morning and outputting in the evening. Instead of having these massive violation spikes we instead have smaller more consistent ones.
The biggest issue with this method is that all the batteries start outputting at the same time and can occur while solar is still active unlike the previous two iterations. While the output is relatively small when you have 100 of them acting together, the result is like the previous discussion but added on top of the solar this time. Because of this we show violations that used to occur in the morning now can occur in the evening. The load can be calculated from the formula below.

\[ P_{\text{total}} = P_{\text{Load}} - P_{\text{Solar}} - P_{\text{battery}} \times N \]

Equation 13 Net demand

Where \( P \) is the real power components and \( N \) is the number of batteries that were used in the calculations. It should be remembered at this point that since we are using a power factor of 1 all considerations are being taken without the reactive component being considered. Since the solar inverter uses a power factor of .8 the arrays will be outputting reactive components into the system checked against only by the existing load.

Of course, this could easily be counteracted by moving the scheduling time up however in keeping with the idea that energy must be depleted during the peak time that will raise the output of each battery and the problem will only intensify in that later time. You could shift the time where it is output to later in the day but that is also outside the bounds of our requirements. Ideally, we would be able to adapt to the grid on the residential side using a smart control and in fact people are already considering the idea for these applications [15].

Overall while this was the least effective for the grid this would still be ideal for the user as it focuses the customer side generated power into the times where the customer demand will be at its highest as well as when the costs of said power would be highest if the local grid
charges peak power demand costs. Additionally, only a small number of units are needed to produce this effect.

Of the original 24 out of specification phases 23 remain leading to a 4% improvement. Since one of the tests did result in additional phase it would be a straight wash.
Chapter 7: Conclusion

In conclusion we have shown that while BESS will not immediately solve the issue of solar variability there is a benefit to both user and on the generation side. BESS can lower and limit both the magnitude and the occurrences of voltage infractions. The maximum current in many cases was also found to be lower than without. BESS allow the use of more solar as well as helping the grid become more stable and reliable reducing power surges. As our grid continues to evolve and the ability for the average residential customer to grow in importance we have shown that both sides of the grid can benefit from the use of BESS.

Local power utilities have begun installing smart air conditioner control monitors for users and giving the user a discount on power. The reason for this is when the power company is experiencing an extreme amount of demand they will take the setting of your thermostat and raise it a few degrees thus shutting off your air conditioner and lowering the overall grid demand. This may sound miniscule but if enough people adopt this then they experience a large load reduction allowing them to maintain reliability without the cost of added backup generators running. Similarly, to our results if enough batteries act in concert you can see that the overall system voltage becomes more reliable and stable. Based upon our findings it is not without reason that the utility company could offer discounts or incentives to adopting BESS into households that may not even have solar installed.

Future work in the field could be the development of better scheduling techniques, the ability to perform analysis on system during power outages, and the scale of these simulations. While Gridlab-D is able simulate items down to the residential level it still needs updates when it comes to the capabilities of batteries.
Better scheduling techniques can be a conglomeration of a few items. Anytime the battery is active is a boon to the user while anytime the battery is inactive it is a cost. Taking the battery and forcing it to constantly charge and discharge is a worthwhile endeavor but ideally you want your unit to be more active. Taking the unit and allowing it to monitor your power factor in real time would allow you to control it and possibly even regulate by injecting reactive power into the system when needed.

Our work focused on using single batteries in houses but in the same vein of better scheduling it is not unheard of to have multiple systems in each house. As such you may begin scheduling one battery to output while the other charges and vice versa. This may sound counterproductive but as was the case with the negative load use there were a few times in the year where the difference between full utilization and missing out on energy was the emplacement of a single battery unit. As was just discussed we could also use a single battery to monitor the power factor of a system while the other focuses on the mundane aspect of power utilization.

A great loss to our project was the inability to simulate the batteries in conditions where power was lost, and the branch would become independent from the rest of the grid. This could be highly destructive to those that require constant power such as small business or those with medical conditions. Under these conditions the battery user could be self-reliant and continue to function throughout the blackout or if the unit was controlled via the distribution side and enough batteries were enabled in the system it is possible to cover short small areas using battery power.

The battery that the simulations were based upon has already changed their production specifications. While initially they stated their overall battery, capacity was 12kWhs and had a depth of discharge of about 10% they now state their battery has a total capacity of 13.5kWhs. Assuming another 10% depth of discharge that would put the overall battery at 15kWhs. Additionally, they state that the max peak draw out of the battery is now 7kW an hour while it can still only maintain a usage draw of
5kW an hour under continuous use. They do not state if the charging rate has changed which is one of the largest constraints to this project. While the change in discharge rate does not really help us as we kept a very small rate of discharge throughout our simulations the capacity of the battery could have lowered all the required batteries and continued to have the same effects upon our results. BESS will continue to advance and change at a rapid pace and will need to be reevaluated often.

Finally, as we mentioned there were multiple drawbacks from a battery standpoint when it comes to the Gridlab-D software. While the language does support two iterations of a battery one of them is a legacy version of the code while the other is difficult to implement on our scale. The addition of even simple batteries would allow the user to perform more complicated simulations and optimizations getting more varied and interesting results. As of this writing the lab was looking at adding more functionality into the battery object in some of their upcoming updates, so it is a necessity. Once these are implemented it would be prudent to consider the results of using batteries on a lower scale. While we were able to study batteries on a grid scale it would be advantageous to study them all the way down to the 120-volt system level.
Appendix A: Base Results

Figure 11 Base result
Figure 12 System with varying load exterior nodes
Figure 13 system with varying load interior nodes
Figure 14 Apparent power of system

Figure 15 Real and imaginary power of system
Appendix C: Auto-Regulator Enabled results

Figure 16 System with auto-regulator exterior nodes
Figure 17 System with auto-regulator interior nodes
Appendix D: Solar Results

Node 611

Figure 18 N611 solar results exterior nodes
Figure 19 N611 solar results interior nodes
Node 634

Figure 20 N634 solar results exterior nodes
Figure 21 N634 solar results interior nodes
Node 645

Figure 22 N645 solar results exterior nodes
Figure 23 N64S solar results interior nodes
Node 646

Figure 24 N646 solar results exterior nodes
Figure 25 N646 solar results interior nodes
Node 652

Figure 26 N652 solar results exterior nodes
Figure 27 N652 solar results interior results
Figure 28 N671 solar results exterior results
Figure 29 N671 solar results interior results
Figure 30 N675 solar results exterior nodes
Figure 31 N675 solar results interior results
Figure 32 N692 solar results exterior nodes
Figure 33 N692 solar results interior nodes
Node 6321

Figure 34 N6321 solar results exterior nodes
Figure 35 N6321 solar results interior nodes
Node 6711

Figure 36 N6711 solar results exterior nodes
Figure 37 N6711 solar results interior results
Distributed solar

Figure 38 Distributed solar results exterior nodes
Figure 39 Distributed solar results interior nodes
Appendix E: Peak Shaving Results

Node 611

Figure 40 N611 Peak shaving results exterior nodes
Figure 41 N611 peak shaving results interior nodes
Node 645

Figure 42 N645 peak shaving results exterior nodes
Figure 43 N645 peak shaving results interior nodes
Node 652

Figure 44 N652 peak shaving results exterior nodes
Figure 45 N652 peak shaving results interior nodes
Figure 46 N671 peak shaving results exterior nodes
Figure 47 N671 peak shaving results interior nodes
Figure 48 N675 peak shaving results exterior nodes
Figure 49 N675 peak shaving results interior nodes
Node 692

**Figure 50** N692 peak shaving results exterior nodes
Figure S1 N692 peak shaving results interior nodes
Node 6321

Figure 52 N6321 peak shaving results exterior nodes
Figure 53: N6321 peak shaving results interior nodes
Figure 54 N6711 peak shaving results exterior nodes
Figure 55 N6711 peak shaving results interior nodes
Distributed peak shaving results exterior nodes

Figure 56 Distributed peak shaving results exterior nodes
Figure 57 Distributed peak shaving results interior nodes
Appendix F: Negative Load Shifting Results

Node 611

Figure 58 N611 negative load shifting results exterior nodes
Figure 59 N611 negative load shifting results interior nodes
Node 645

Figure 60 N645 negative load shifting results exterior nodes
Figure 61 N645 negative load shifting results interior nodes
Node 652

Figure 62 N652 negative load shifting results exterior nodes
Figure 63 N652 negative load shifting results interior nodes
Figure 64 N671 negative load shifting results exterior nodes
Figure 65 N671 negative load shifting results interior nodes
Node 675

Figure 66 N675 negative load shifting results exterior nodes
Figure 67: N675 negative load shifting results interior nodes.
Figure 68 N692 negative load shifting results exterior nodes
Figure 69 N692 negative load shifting results interior nodes
Node 6321

Figure 70 N6321 negative load shifting results exterior nodes
Figure 71 N6321 negative load shifting results interior nodes
Node 6711

Exterior nodes

Voltage in p.u.

Time in hours

Figure 72 N6711 negative load shifting results exterior nodes
Figure 73 N6711 negative load shifting results interior nodes
Distributed

Figure 74 Distributed negative load shifting results exterior nodes
Figure 75 Distributed negative load shifting results interior nodes
Appendix G: Time of Use Results

Node 611

![Figure 76 N611 time of use results exterior nodes](image)

*Figure 76 N611 time of use results exterior nodes*
Figure 77 N611 time of use results interior nodes
Figure 78: N645 time of use results exterior nodes
Figure 79 N64S time of use results interior nodes
Figure 80 N652 time of use results exterior nodes
Figure 81 N652 time of use results interior nodes
Node 671

Figure 82 N671 time of use results exterior nodes
Figure 83 N671 time of use results interior nodes
Figure 84 N675 time of use results exterior nodes
Figure 85 N675 time of use results interior nodes
Figure 86 N692 time of use results exterior nodes
Figure 87 N692 time of use results interior nodes
Figure 88 N6321 time of use results exterior nodes
Figure 89 N6321 time of use results interior nodes
Node 6711

Figure 90 N6711 time of use results exterior nodes
Figure 91 N6711 time of use results interior nodes
Figure 92 Distributed time of use results exterior nodes
Figure 93: Distributed time of use results interior nodes
Bibliography


Curriculum Vitae

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Education

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Bachelor of Science – Electrical Engineering, December 2013

Thesis

Simulating distributed battery and solar array placement for voltage regulation

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Dr. Robert Boehm

Dr. Brendan Morris

Dr. Yingtao Jiang