Modeling and Analysis of the Distribution Grid in the Presence of Electric Vehicles and Energy Storage Systems

Stephen Michael Cialdea
Worcester Polytechnic Institute

Follow this and additional works at: https://digitalcommons.wpi.edu/etd-theses

Repository Citation
https://digitalcommons.wpi.edu/etd-theses/500

This thesis is brought to you for free and open access by Digital WPI. It has been accepted for inclusion in Masters Theses (All Theses, All Years) by an authorized administrator of Digital WPI. For more information, please contact wpi-etd@wpi.edu.
Modeling and Analysis of the Distribution Grid in the Presence of Electric Vehicles and Energy Storage Systems

By

Stephen M. Cialdea

A Thesis
Submitted to the Faculty
Of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree in Master of Science
In
Electrical and Computer Engineering
May 1st, 2014

Approved:

Professor Alexander E. Emanuel

Professor John A. Orr
Table of Contents

Table of Figures .................................................................................................................. 3
Table of Tables ..................................................................................................................... 5
Table of Equations ................................................................................................................. 6

1 Introduction ..................................................................................................................... 8

2 Background ..................................................................................................................... 10

  2.1 Electric Vehicles ......................................................................................................... 10
      2.1.1 History of EVs ................................................................................................... 10
      2.1.2 Current EV Technology ................................................................................... 13
      2.1.3 EV Proliferation ............................................................................................... 17
      2.1.4 Effects on Distribution Grid ............................................................................ 20

  2.2 Outages and Feeder Upgrade ..................................................................................... 22

  2.3 Economic Justification Methods .............................................................................. 25

  2.4 Load Profiles ............................................................................................................. 26

  2.5 The Cost of Electricity ............................................................................................... 31

  2.6 Large Capacity Energy Storage Systems .................................................................. 33
      2.6.1 Energy Storage Technologies ......................................................................... 33
      2.6.2 Use Cases ......................................................................................................... 35

3 Development of the Modeling System .......................................................................... 38

  3.1 Substation and End Blocks ....................................................................................... 39

  3.2 Line Block ................................................................................................................ 41

  3.3 Transformer Block .................................................................................................... 43

  3.4 Generation/Load Block ............................................................................................ 45

  3.5 Capacitor Block ........................................................................................................ 45

  3.6 Battery Energy Storage System Block ..................................................................... 46

  3.7 Economic Calculations .............................................................................................. 47

4 BESS Algorithms ............................................................................................................ 49

  4.1 Dynamic Programming for Optimum Economic Operation ..................................... 49

  4.2 Power Flow Smoothing ............................................................................................ 54

  4.3 Peak Shaving ............................................................................................................. 62

5 Stability Enhancement .................................................................................................... 64

6 Test Feeder Configuration ............................................................................................... 67

7 Results and Analysis ....................................................................................................... 68

  7.1 Base Case .................................................................................................................. 69

  7.2 Electric Vehicle Penetration ...................................................................................... 70
7.3 Photovoltaic Generation........................................................................................................73
7.4 System with BESS ...............................................................................................................76
7.5 Electric Vehicle Penetration and Distributed Generation......................................................78
7.6 BESS and Electric Vehicle Penetration ..................................................................................79
7.7 BESS, Electric Vehicle Penetration, and Photovoltaic Generation ..........................................81
7.8 BESS for Stability ..................................................................................................................83
   7.8.1 Simple Stability Example ..............................................................................................88
8 Conclusions ..............................................................................................................................97
References .....................................................................................................................................99
### Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EV Timeline</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Example Charging Profile of Nissan LEAF with Assumed Ramp Rates</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>EV and PHEV Sales per Month</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Cumulative EV and PHEV Sales to Date</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Residential Load Profile</td>
<td>28</td>
</tr>
<tr>
<td>7</td>
<td>Small Commercial Load Profile</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>Medium Commercial Load Profile</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>Medium Industrial Load Profile</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>Large Industrial Load Profile</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>2012 Eastern Massachusetts LMP</td>
<td>32</td>
</tr>
<tr>
<td>12</td>
<td>Model Signal Flow</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>Ideal Response</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>Tuned Response</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>Substation Parameter Prompt</td>
<td>41</td>
</tr>
<tr>
<td>16</td>
<td>Line Block Signal Flow Diagram</td>
<td>42</td>
</tr>
<tr>
<td>17</td>
<td>Line Block Parameter Prompt</td>
<td>42</td>
</tr>
<tr>
<td>18</td>
<td>Transformer Parameter Prompt</td>
<td>44</td>
</tr>
<tr>
<td>19</td>
<td>Load/Generation Block Signal Flow Diagram</td>
<td>45</td>
</tr>
<tr>
<td>20</td>
<td>Battery Energy Storage System Parameter Prompt</td>
<td>46</td>
</tr>
<tr>
<td>21</td>
<td>Battery Energy Storage System Block Signal Flow Diagram</td>
<td>47</td>
</tr>
<tr>
<td>22</td>
<td>Simple Map</td>
<td>49</td>
</tr>
<tr>
<td>23</td>
<td>Labeled Simple Map</td>
<td>50</td>
</tr>
<tr>
<td>24</td>
<td>Dynamic Programming Map for BESS</td>
<td>53</td>
</tr>
<tr>
<td>25</td>
<td>Smoothing Algorithm Block Diagram</td>
<td>54</td>
</tr>
<tr>
<td>26</td>
<td>Smoothing Algorithm Flowchart</td>
<td>55</td>
</tr>
<tr>
<td>27</td>
<td>Consumption Diagram</td>
<td>58</td>
</tr>
<tr>
<td>28</td>
<td>Production Diagram</td>
<td>61</td>
</tr>
<tr>
<td>29</td>
<td>Faulted Load Curves</td>
<td>65</td>
</tr>
<tr>
<td>30</td>
<td>Feeder Configuration Diagram</td>
<td>67</td>
</tr>
<tr>
<td>31</td>
<td>Base Case Load and Voltage Profile</td>
<td>69</td>
</tr>
</tbody>
</table>
Table of Tables

Table 1: Popular Electric and Plug in Electric Vehicle Specifications [7-12] .................................................. 14
Table 2: Charger Levels Voltage Class and Typical Charge Rate ................................................................. 15
Table 3: Charging Times for Popular Vehicle Models ......................................................................................... 15
Table 4: Outage Indexes ..................................................................................................................................... 22
Table 5: Outage Index Statistics ....................................................................................................................... 23
Table 6: Momentary Outage Costs Per Installed kW Load .................................................................................. 23
Table 7: Sustained Outage Costs Per kW Installed Load for Given Time Periods ............................................. 24
Table 8: Energy storage technologies and their characteristics [37, 38] ................................................................. 33
Table 9: Use Case Categories ............................................................................................................................. 37
Table 10: Decision Table for D4 ....................................................................................................................... 51
Table 11: Decision Table for D3 ....................................................................................................................... 51
Table 12: Decision Table for D2 ....................................................................................................................... 52
Table 13: Decision Table for D1 ....................................................................................................................... 52
Table 14: Smoothing Algorithm Symbol Definitions ........................................................................................... 56
# Table of Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single Payment Present Worth Equation</td>
</tr>
<tr>
<td>2</td>
<td>Annuity Payment Present Worth Equation</td>
</tr>
<tr>
<td>3</td>
<td>Benefit-Cost Ratio Equation</td>
</tr>
<tr>
<td>4</td>
<td>Mean of a Discrete Data Set</td>
</tr>
<tr>
<td>5</td>
<td>Standard Deviation of a Discrete Data Set</td>
</tr>
<tr>
<td>6</td>
<td>95% Confidence Interval</td>
</tr>
<tr>
<td>7</td>
<td>Current Calculation</td>
</tr>
<tr>
<td>8</td>
<td>Voltage Drop Calculation</td>
</tr>
<tr>
<td>9</td>
<td>Active Power Loss Calculation</td>
</tr>
<tr>
<td>10</td>
<td>Reactive Power Loss Calculation</td>
</tr>
<tr>
<td>11</td>
<td>Transformer Per Unit to Resistance</td>
</tr>
<tr>
<td>12</td>
<td>Transformer Per Unit to Reactance</td>
</tr>
<tr>
<td>13</td>
<td>Impedance Angle</td>
</tr>
<tr>
<td>14</td>
<td>Percent Impedance to Percent Resistance</td>
</tr>
<tr>
<td>15</td>
<td>Percent Impedance to Percent Resistance</td>
</tr>
<tr>
<td>16</td>
<td>Rate of Change is Outside Limits</td>
</tr>
<tr>
<td>17</td>
<td>Rate of Change is Positive</td>
</tr>
<tr>
<td>18</td>
<td>BESS Can Consume Enough Energy to Limit Rate of Change</td>
</tr>
<tr>
<td>19</td>
<td>BESS Can Consume Enough Energy for One Time Step</td>
</tr>
<tr>
<td>20</td>
<td>BESS Output</td>
</tr>
<tr>
<td>21</td>
<td>BESS SOC</td>
</tr>
<tr>
<td>22</td>
<td>BESS Can Not Consume Enough Energy for One Time Step</td>
</tr>
<tr>
<td>23</td>
<td>BESS Can Not Consume Enough Power to Limit Rate of Change</td>
</tr>
<tr>
<td>24</td>
<td>BESS Can Consume Available Power Capacity for One Time Step</td>
</tr>
<tr>
<td>25</td>
<td>BESS Output</td>
</tr>
<tr>
<td>26</td>
<td>SOC Calculation</td>
</tr>
<tr>
<td>27</td>
<td>Renewable Power Rate of Change is Negative</td>
</tr>
<tr>
<td>28</td>
<td>BESS Can Supply Enough Power</td>
</tr>
<tr>
<td>29</td>
<td>BESS Has Enough Energy to Supply</td>
</tr>
<tr>
<td>30</td>
<td>BESS Output</td>
</tr>
<tr>
<td>31</td>
<td>SOC Calculation</td>
</tr>
</tbody>
</table>
1 Introduction

Many new technologies are being introduced to the electrical power grid at the distribution voltage level. These technologies include electric vehicles (EVs), distributed generation, and battery energy storage systems (BESSs). As these technologies proliferate the electric power grid becomes an ever more complicated system. This thesis investigates how these various technologies can be harmoniously integrated into the electric grid.

Electric vehicles have a long, but sparse history; their genesis dates back to the 1830s. However, EVs have become moderately successful only in the past five to ten years. This technology can potentially represent a large amount of load to be added to the electric grid. This large load will also be, for the most part, added to a specific time period of the evening that coincides with the peak demand of the current system. Distributed renewable generation is also becoming a more and more popular technology, particularly photovoltaic (PV). However, this technology produces power during the middle of the day and does not aid in relieving the peak demand that is increased by the onset of large quantities of EV charging.

With the increase in distributed generation it is becoming likely to see load centers that are electrically self-sufficient in a micro grid. These micro grids have the ability to operate in isolation from the macro grid or independently. However, like the system we are seeing the macro grid develop into, these systems are bi-directional and can be comprised of numerous uncontrollable sources in the form of renewable generation. This can result in a system that does not have the proper inertia to recover from a fault within its own system while running in isolation from the grid.

Energy storage provides two key functions in a microgrid, an opportunity to shift this renewable energy to a time when it can be better used, and for added post-fault stability. By using energy storage in a microgrid to shift renewable energy to peak demand periods the swing generation required becomes smaller. For stability purposes, the energy storage can be used to balance mechanical and electrical power directly after a fault condition while the swing generator’s governor adjusts to the new value. In normal systems there would be a large number of generation in place that could perform this task, but in a microgrid there is a limited amount of swing generation, or inertia.

Typical load-flow programs run a single scenario representing a point in time, but what is needed is a tool that models and simulates the performance of a distribution system over periods of time: days, weeks, or months. The creation of this tool is documented in this report. This tool can then be used to
study the effects that EVs and renewable generation have on feeders and how BESS can aid in reducing their negative impacts. This tool will also entail economic calculations to investigate the economic feasibility of the installation of a BESS.

To perform these studies, in depth background research into EV and BESS technology was completed. The technology is presented so that representative information can be used in the simulation tool to investigate a method of determining the maximum percentage of load of EV a feeder can handle, how renewable energy can aid or hinder this percentage, and how a BESS can be useful in these scenarios.

The impact a BESS can have on the stability of a micro grid is carried out using mathematical models. These mathematical models will focus on the electrical transients only since reliability has a binary correlation to cost with the only possible results of failure and failure avoidance. The goal of this study is to determine what power and energy rating battery must have given a micro grid load size and configuration. This study must be run with given the worst case parameters, which is the heaviest load the micro grid will see. Therefore, the importance of reducing these load swings shown with the use of the BESS in the simulation tool will be stressed. With the combination of sizing needed for reliability and economic gains determined, the addition of the BESS to the system can be economically studied.

The objectives of this research are to accomplish the following tasks:

1. Perform an in depth background research of all pertinent topics,
2. Create a simulation environment where the electrical and economic performance of distributed generation and energy storage can be studied over time periods of days/weeks/months/years,
3. Create algorithms that optimize the use of energy storage in various use cases,
4. Use the simulation tool to investigate the impact that the use of optimum performing energy storage has in distribution feeders,
5. Study the effects energy storage can have on stability in low inertia systems (microgrids) in post-fault conditions,
2 Background

This chapter introduces the background information relevant to the goals of this thesis. A brief history of EVs will be given as well as analysis of their current technological status. The amount of proliferation and projected proliferation will be presented as well as their possible effects on the distribution grid. This information will give a firm basis for the types of impacts that can potentially be mitigated with distributed generation and/or energy storage.

The various technologies of energy storage will be explored and summarized. A comprehensive list of known uses cases will also be presented. The use cases particular to this research will be explained in depth and paired with certain technologies that are fitting. This background will provide the restraints for power and energy capacities that may be used while performing studies.

The costs associated with outages and feeder upgrades will be shown. In situations where energy storage is used to avoid outages or defer system upgrade these costs can be used in calculating the avoided cost and help to economically justify the energy storage installation. Therefore, economic justification methods will also be presented. Another cost avoidance point is found when using energy storage in an energy time-shift function. As a basis of this study the structure and typical costs of electricity are explained with a focus on the New England area in the United States.

2.1 Electric Vehicles

This section provides an overview of the pertinent aspects of electric vehicles that must be taken into account to properly model and research systems that include them. The areas presented include, the history of EVs, proliferation to date, current technology, and effects that arise when they are connected in bulk to the electric grid.

2.1.1 History of EVs

Although the use of electric vehicles proliferation has become significant recently, there is a rich history of inventors and businessmen that have attempted to make these vehicles practical. This section will present a brief history of the electric vehicle. Figure 1 shows a timeline of notable milestones to be discussed.
Hans Christian Orsted discovered that electric current creates magnetic fields in the 1820s when noticing a compass needle moving near one of his experiments when energized [1]. This work would be extended later by inventors such as Michael Faraday, Joseph Henry, William Sturgeon, Mortiz Hermann Jacobi, and Thomas Davenport whom would create numerous electro-mechanical devices, including various forms of electric motors in the 1830s. Thomas Davenport’s brush and commutator direct current motor/generator design would become well used in trains/trolleys and Thomas Edison’s power generation stations during the 1830s [2].

However, one of the very first electric vehicles can be tracked back to a Scottish man named Robert Anderson in 1832. However, this electric carriage was powered by non-rechargeable batteries and therefore did not succeed. The Electric Vehicle Company, a holding company of various electric car companies, would be one of the first marginally successful attempts to commercialize EVs in the late 1890s mainly using the “Electrobat” and the Riker Electric Vehicle [3]. The Electrobat was a lead-acid battery based vehicle created by an engineer and chemist, Henry G. Morris and Pedro G. Salom respectively. The Riker Electric Vehicle was created by Andrew L. Riker.
Moving into the 1900s the electric car would start to see competition from the internal combustion engine due to the abundance of cheap gasoline and the ability to fill a gas tank in a fraction of the time necessary to charge a battery. In 1908 the Model T, produced by Ford, would dominate the personal transportation sector in the United States. During the next 60-70 years the internal combustion engine would take hold of the transportation market with many of the car manufacturers still producing vehicles today, coming into existence [4].

A new hope for electric vehicles was seen in the fuel shortages of the 1970s that turned the public’s view back towards electric vehicles. However, this hope was fleeting as the fuel shortage would pass with still no practical electric vehicles that could compete with the range, ease, and affordability of internal combustion driven vehicles until 1996 when GM released the EV1. The EV1 boasted approximately an 80 mile driving distance on a single charge of its lead-acid battery pack. It became popular and sought after by the public but was found to not be profitable by GM and the program was canceled in 2003 [5].

In the 2000s the most the most notable electric cars would be the Toyota Prius and the Tesla Roadster. The Toyota Prius would quickly gain popularity as a hybrid electric-vehicle that makes use of both an electric motor and an internal combustion motor for maximum fuel economy. The Tesla Roadster was an exotic and expensive electric vehicle but was famous due to the high speeds it could attain with an acceptable driving distance of approximately 120 miles. This would be considered the first commercially available sports electric vehicle.

As gas prices and environmental concerns increased throughout the 2000s and into the 2010s, so did the interest in electric vehicles by consumers and manufacturers where electric and hybrid-electric vehicles such as the Toyota Prius’, Nissan LEAFs, and Chevrolet Volts became common to see on the road. By 2014, many major car manufacturers would have an electric and/or hybrid-electric model available and most manufacturers without an electric option are reporting their intention to release models within a few years.
2.1.2 Current EV Technology

Electric vehicle technology is under constant research and becoming more and more practical over time. This section will look at current electric vehicle technology so appropriate assumptions can be made while studying systems incorporating EVs. The pertinent information that must be investigated is vehicle range, battery size (kWh), charge time, and charge profile.

The range of the vehicles will be important when making estimations of what types of vehicles will be used in certain areas, whether it be city, suburban, or rural. Figure 2 displays the distribution of commute time of United States. Each month is divided in an effort to capture any seasonal jobs that may impact commute distance.

![United States Commute Time Census Data](image)

**Figure 2: United States Commute Time Census Data [6]**

By coupling the necessary commute distances with the number of expected EVs on a feeder, an approximate EV charging demand can be determined. Therefore, an overview of popular electric vehicles available in the United States and their corresponding driving range is shown in Table 1.
<table>
<thead>
<tr>
<th>Make and Model</th>
<th>Cost</th>
<th>Range(^1)</th>
<th>Battery Size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHEVs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>$39,145</td>
<td>38mi</td>
<td>16kWh</td>
</tr>
<tr>
<td>Fisker Karma</td>
<td>$102,000</td>
<td>50mi</td>
<td>20 kWh</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>$32,000</td>
<td>15mi</td>
<td>4.4 kWh</td>
</tr>
<tr>
<td><strong>EVs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMW ActiveE</td>
<td>N/A</td>
<td>94mi</td>
<td>32 kWh</td>
</tr>
<tr>
<td>Coda Automotive CODA Sedan</td>
<td>$37,250</td>
<td>88mi</td>
<td>31 kWh</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>$39,200</td>
<td>76mi</td>
<td>23 kWh</td>
</tr>
<tr>
<td>Mitsubishi “I”</td>
<td>$39,125</td>
<td>81mi</td>
<td>16 kWh</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>$35,200</td>
<td>90mi</td>
<td>24 kWh</td>
</tr>
<tr>
<td>Tesla Motors Model S</td>
<td>$57,400</td>
<td>300mi</td>
<td>40 kWh</td>
</tr>
</tbody>
</table>

\(^1\)Range represents the electric range only. PHEVs have a higher overall range when other fuel source is taken into account. However, this column represents the full range for EVs since no other fuel source is available.

Table 1: Popular Electric and Plug in Electric Vehicle Specifications [7-12]

The results in Table 1 are divided into “PHEVs” and “EVs”. These stand for Plugin Hybrid Electric Vehicles and Electric Vehicles. PHEVs make use of electric propulsion and fossil fuels, meaning they can run by an electric motor or use reserve fossil fuel in a combustion motor if the electrical charge is depleted, whereas EVs run purely on electrically stored energy. PHEVs tend to have lower electrical mileage range capability vs. EVs because of the option of running on a combustion motor is often used. It should be noted that PHEVs usually have a higher overall range than EVs when taking into account the full range of the electric and combustion engines with full fuel sources. EVs have the benefit of having larger electric ranges than the PHEVs, but require a charging station to refuel instead of the ability to stop at the numerous gas stations on the road to quickly refill the tank. Therefore, having a pure EV requires more trip planning than a PHEV but can potentially save the consumer money if planned correctly.

There are three classes or levels of chargers that provide the ability to charge the EVs faster by increasing the charging voltage. The voltages are standardized, however the current draw allowed from the charger or the vehicle are not. Table 2 provides guidelines published by the United States
Department of Energy of typical charging rates to be expected when charging with various levels of chargers [13].

<table>
<thead>
<tr>
<th>Charger Level</th>
<th>Voltage</th>
<th>Typical Charge Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>110 Volts</td>
<td>2-5 miles per hour charging</td>
</tr>
<tr>
<td>Level 2</td>
<td>208-240 Volts (220V Nominal)</td>
<td>10-20 miles per hour charging</td>
</tr>
<tr>
<td>Level 3</td>
<td>440 Volts</td>
<td>60-80 miles per 20 min. charging</td>
</tr>
</tbody>
</table>

*Table 2: Charger Levels Voltage Class and Typical Charge Rate*

Therefore, Table 1’s listing of popular electric vehicles can be put into terms of charge time of the various popular vehicles.

<table>
<thead>
<tr>
<th>Make and Model</th>
<th>Range</th>
<th>Charge Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td><strong>PHEVs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>38mi</td>
<td>13 h</td>
</tr>
<tr>
<td>Fisker Karma</td>
<td>50mi</td>
<td>17 h</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>15mi</td>
<td>5 h</td>
</tr>
<tr>
<td><strong>EVs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMW ActiveE</td>
<td>94mi</td>
<td>31 h</td>
</tr>
<tr>
<td>Coda Automotive CODA Sedan</td>
<td>88mi</td>
<td>29 h</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>76mi</td>
<td>25 h</td>
</tr>
<tr>
<td>Mitsubishi “i”</td>
<td>81mi</td>
<td>27 h</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>90mi</td>
<td>30 h</td>
</tr>
<tr>
<td>Tesla Motors Model S</td>
<td>300mi</td>
<td>100 h</td>
</tr>
</tbody>
</table>

*Table 3: Charging Times for Popular Vehicle Models*

It is assumed that EV charging will have a small ramp until reaching the nominal charging rate. After this ramp the rate will stay approximately at rated rate until a similar ramp down to zero when the battery is at full capacity. This assumption is based on actual charge profiles [12, 14]. It is also assumed
that the charger inverter technologies allows for any charge rate below the rated charging level. An example charge profile of the Nissan LEAF with a near depleted battery is shown in Figure 3.

![Charge Profile](image)

Figure 3: Example Charging Profile of Nissan LEAF with Assumed Ramp Rates

These values will be the basis for the power demands of EVs and PHEVs. The next section will investigate the quantity of EVs and PHEVs are currently in society, the distribution of types, and their growth projections so that large scale estimates of power consumption demands can be made.
2.1.3 EV Proliferation

This section investigates the nature of electric vehicles’ increasing popularity. Information such as the number of EVs and PHEVs on the road currently, the distribution of types of vehicles, and their proliferation projections will be presented. There are numerous factors that contribute to electric vehicle’s proliferation including government incentives, social opinions, development of technology, the cost of fuel, and the cost of electricity.

There are numerous incentives and grants available depending on the state of residence for owners of EVs and PHEVs provided by the state government and utilities or private companies. The major federal incentive is the Qualified Plug-In Electric Drive Motor Vehicle Tax Credit, which can provide a tax credit from $2,000-7,500 depending on vehicle ratings. The United States Department of energy maintains a searchable database of all available incentives by state and technology [15]. Although incentives can provide some support in buying a vehicle, they are small in comparison to the cost of the vehicle.

There are also government acts being put in place in an effort to reduce air pollution by encouraging EV ownership. The most prominent is The Clean Air Act, which regulates emissions and mandates of percentages of clean fuel vehicles in government and business owned vehicle fleets [16]. The United States Department of Energy has also produced the “One Million Electric Vehicles By 2015” report. This policy calls for $2.4 billion dollars to be loaned to car factories and another $2 billion of grants to be awarded to EV technology research under The Recovery Act. Figure 4 shows the monthly sales of EVs historically [17].
It can be seen by inspection that EVs and PHEVs are becoming increasingly popular and are EVs now being purchased at nearly the same amount of PHEVs. Since EVs have a larger draw on the electric grid, this is reason to believe that the electric car market will soon be making a bigger impact on the grid’s operation. A cumulative look at EV and PHEV sales can be seen in Figure 5.
This shows an overall increasing rate of vehicles that charge or can be charged via the electric grid. Therefore, it can be assumed that this trend will continue and the electric vehicle's impact on the grid will become more prominent at an increasing rate.
2.1.4 Effects on Distribution Grid

As the proliferation of EVs increases, their demand on the electrical grid will increase due to charging needs. The charging demand of these vehicles will be, for the most part, at the same time assuming that they will need to be charged as owners return from work. Therefore, for a particular feeder the demand will be increased significantly during the charging period.

An increased current may exceed the cable’s rating and therefore increase the cable’s temperature above the thermal rating. Once above the thermal limit the cable will be aged and in danger of failure. Additionally, there may be equipment on the feeder or in the distribution substation, such as transformers and circuit breakers, which may be damaged from the high current if not rated properly for the increase in demand [18]. In order to ensure that these problems do not occur, careful studies must be carried out to determine whether the current transmission and distribution systems can handle the increased demand. It is assumed that generation can be increased to meet the demand, but at a higher price. This topic is discussed in a later section.

Voltage drop on a feeder due to the influx of electric vehicles is also a concern to the electric grid. There have been studies that have shown that on small scale feeders electric vehicle proliferation will impact voltage drops only a few percent per unit (at 30% of vehicles being electric) [19]. However, this depends heavily on the particular feeder configuration and current demand. Mitigation of this effect includes battery storage, feeder upgrade, load shedding, and charge scheduling (also known as smart charging). However, justifications for these mitigations for can be difficult to quantify since voltage sags does not always directly relate to a cost. These sags may create damage that goes unnoticed to equipment over time, which may lead to premature failure of the equipment at a much later date.

Increasing EV charging will also increase losses due to the additional current [20]. Since the calculation for electrical loss includes the term of squared current, even slight increases in current can cause a significant increase in losses. These losses are, in some sense, unavoidable since the current must reach the electric vehicles. However, by decreasing the peak current on the feeder caused by the charging of the electric vehicles, the losses can be minimized. This minimization will also minimize the voltage drop on the feeder, since the voltage drop is directly related to current. However, since the price of the energy lost can be calculated, the justification process is straightforward in this case.
Included in the price of electricity to customers is a congestion charge. When areas of transmission or distribution carry close to their maximum rated capacities, the price of the energy increases since no additional power can be transmitted through that particular transmission path. If feeders that were not originally designed for high penetrations of electric vehicles are inundated with them, congestion can occur [21]. This increase in energy price will make the justification of electric vehicles less optimistic and may not allow them to charge at the desired times.

A possible way to decrease congestion is to find the optimum placement of charging stations and/or energy storage. The optimum placement of these chargers tested on the IEEE 123 node feeder was found to degrease the minimum voltage by approximately 5% per unit [22]. This is a significant decrease in voltage drop, but is also heavily dependent on particular feeder characteristics.

Another possible way to decrease the peak demand is to create incentives for customers to decrease demand during peak periods. However, this option requires strict regulation and communication between the various parties [23]. This method of mitigation also assumes that there are enough customers that are willing and/or able to participate in the program. However, it can be applicable to all types of customers, whether it is residential, commercial, or industrial and is already in use in some areas of the country.

The most substantial mitigation to the negative effects that electric vehicle charging has on the transmission and distribution systems is smart charging. Smart charging is the scheduling of vehicle charging at different times or charging at rates below the maximum power rating of the chargers. This allows for certain vehicles within a fleet to be fully charged when necessary while minimizing the effects on the grid as a whole. It has been found to be able to reduce the voltage drop of over 50% penetration to a level as if it were 10% penetration without using smart charging [24].

Smart charging is used over a particular area or feeder. The vehicles within this area may have to sacrifice their preferred charging time slightly to accommodate the smart charging plan. However, if smart charging were coupled with large capacity battery energy storage, the effect of smart charging may be minimal. For this system to be realized, battery storage would be applied downstream of areas suffering from congestion. These are usually junction points that are providing multiple feeder branches. The energy storage would be charged during light loading periods and discharged downstream of the problem area to relieve some of the stress on the system.
Outages and Feeder Upgrade

Outages can be a costly result of feeder overload and estimates show that outages cost $79 billion per year in the United States alone [25]. As discussed in the previous section, the increased number of EVs can put strain on distribution systems and may push the system above rated limits on peak days. Applying mitigation topics discussed in the previous section can help to prevent these outages, but to justify the capital costs associated with these systems the cost of outages must be determined. The three indexes that statistically summarize the frequency and duration of outages can be seen in Table 4. Utilities are mandated to keep this data on record [26].

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIDI</td>
<td>System Average Interruption Index is the average number of minutes of outage per customer annually</td>
</tr>
<tr>
<td>SAIFI</td>
<td>System Average Interruption Frequency Index is the average frequency of interruption per customer</td>
</tr>
<tr>
<td>MAIFI</td>
<td>Momentary Average Interruption Frequency Index is the average number of momentary outages per customer</td>
</tr>
</tbody>
</table>

Table 4: Outage Indexes

These statistics divided into regions and costs associated with outage types are seen in Table 5 through Table 7. In this table Customer Average Interruption Duration Index (CAIDI) is reported which is the SAIDI divided by the SAIFI [27]. Since SAIDI is the average number of minutes a customer experiences annually in a cumulative term, dividing by the frequency per customer will yield the average duration of a single outage per customer.
<table>
<thead>
<tr>
<th>Region</th>
<th>CAIDI (Minutes)</th>
<th>SAIFI (Freq./Cust.)</th>
<th>SAIDI (Min./Cust.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Average</td>
<td>88</td>
<td>1.2</td>
<td>106</td>
</tr>
<tr>
<td>Northeast</td>
<td>119</td>
<td>1.1</td>
<td>131</td>
</tr>
<tr>
<td>Southeast</td>
<td>115</td>
<td>1.0</td>
<td>115</td>
</tr>
<tr>
<td>North Central</td>
<td>79</td>
<td>0.8</td>
<td>63</td>
</tr>
<tr>
<td>South Central</td>
<td>73</td>
<td>1.3</td>
<td>95</td>
</tr>
<tr>
<td>Mountain</td>
<td>86</td>
<td>1.1</td>
<td>95</td>
</tr>
<tr>
<td>Northwest</td>
<td>88</td>
<td>1.2</td>
<td>105</td>
</tr>
<tr>
<td>Southwest</td>
<td>84</td>
<td>0.8</td>
<td>65</td>
</tr>
<tr>
<td>California</td>
<td>115</td>
<td>1.2</td>
<td>138</td>
</tr>
</tbody>
</table>

1The CAIDI (Consumer Average Interruption Duration Index) is the SAIDI divided by the SAIFI and represents the average number of minutes of customer interruption.

Table 5: Outage Index Statistics

<table>
<thead>
<tr>
<th>$/kW1</th>
<th>Average</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>$0.10</td>
<td>$0.60</td>
</tr>
<tr>
<td>Small Commercial/Industrial</td>
<td>$0.42</td>
<td>$2.52</td>
</tr>
<tr>
<td>Large Commercial/Industrial</td>
<td>$1.40</td>
<td>$14.00</td>
</tr>
</tbody>
</table>

1Units in dollars per kW capacity installed

Table 6: Momentary Outage Costs Per Installed kW Load
<table>
<thead>
<tr>
<th>$/kW¹</th>
<th>15 Min.</th>
<th>30 Min.</th>
<th>1 Hr.</th>
<th>2 Hr.</th>
<th>4 Hr.</th>
<th>8 Hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>$0.05</td>
<td>$0.60</td>
<td>$2.60</td>
<td>$3.95</td>
<td>$5.30</td>
<td>$5.60</td>
</tr>
<tr>
<td>Small C&amp;I</td>
<td>$8.65</td>
<td>$16.01</td>
<td>$23.37</td>
<td>$48.91</td>
<td>$117.76</td>
<td>$189.23</td>
</tr>
<tr>
<td>Large C&amp;I</td>
<td>$4.79</td>
<td>$7.46</td>
<td>$10.12</td>
<td>$17.96</td>
<td>$36.94</td>
<td>$68.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$/kW¹</th>
<th>15 Min.</th>
<th>30 Min.</th>
<th>1 Hr.</th>
<th>2 Hr.</th>
<th>4 Hr.</th>
<th>8 Hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>$0.30</td>
<td>$3.60</td>
<td>$15.60</td>
<td>$23.70</td>
<td>$31.80</td>
<td>$33.60</td>
</tr>
<tr>
<td>Small C&amp;I</td>
<td>$51.91</td>
<td>$96.08</td>
<td>$140.25</td>
<td>$293.48</td>
<td>$706.57</td>
<td>$1,135.40</td>
</tr>
<tr>
<td>Large C&amp;I</td>
<td>$28.73</td>
<td>$44.73</td>
<td>$60.74</td>
<td>$107.79</td>
<td>$221.62</td>
<td>$410.16</td>
</tr>
</tbody>
</table>

¹Units in dollars per kW capacity installed

Table 7: Sustained Outage Costs Per kW Installed Load for Given Time Periods

This information provides geographical statistics for the frequency for momentary outages (MAIFI), frequency of outages with duration (SAIFI), and their average duration (CAIDI). Momentary outages are created by a fault that is cleared by reclosing and does not correspond to feeder overloading. Prolonged outages are the result of a failure that must be physically repaired. These can be from a downed cable or fixed object creating a fault. It is rare for an outage to occur on a feeder due to continuous overload because the owning entity will upgrade the line before this condition occurs. The costs associated for this upgrade or construction is assumed to be $450,000/mi or $600,000, respectively [28].
2.3 Economic Justification Methods

The two economic methods that will be used in this document are the benefit-cost ratio method and the present worth method [29]. The present worth method calls for all cash flows to be reverted to its worth value at a reference time given a static interest rate, while the benefit-cost ratio method calculates the ratio of benefits over costs.

By using the present worth method the cost of various scenarios can be compared easily or the minimum attractive rate of return (MARR) of any scenario in particular can be calculated. There are two types of future cash flows. A single payment cash flow is a one-time cost or savings and the present value can be calculated using Error! Reference source not found.. An annuity is a reoccurring cost or savings of the same value at periodic intervals and the present value can be calculated using . However, this can also be calculated by iterating the single payment present worth calculation for each payment of the annuity. To complete the present worth method, all costs and benefits are found in present value and summed using these equations.

\[
P = F \cdot C_{SPWF} = F(1+i)^{-N} \quad (1)
\]

\[
P = A \cdot C_{USWF} = A \left[ \frac{(1+i)^N - 1}{i(1+i)^N} \right] \quad (2)
\]

Where

- \( A \) is the dollar amount of the annuity
- \( C_{SPWF} \) is the single payment present worth factor
- \( C_{USWF} \) is the uniform series present worth factor
- \( F \) is the dollar amount of the single cash flow at future value
- \( i \) is the interest rate of the compounding interval
- \( N \) is the number of compounding intervals
- \( P \) is present worth

The cost-ratio sums all of the benefits and divides that sum by the sum of costs. Therefore, if the benefit-cost ratio is greater than 1, the project is justified. The benefit-cost ratio can be seen in .
\[
B - C \text{ Ratio} = \frac{PW(\text{Benefits})}{PW(\text{Costs})} = \frac{PW(B)}{I - PW(MV) + PW(O&M)}
\]  

(3)

Where

- \(PW(*)\) Is the present worth of a cash flow, represented by a “*” in the notation
- \(B\) Are the benefits of the project in dollars
- \(MV\) Is the value of the equipment at the end of its life
- \(O&M\) Are the operation and maintenance costs
- \(I\) Is the initial investment in dollars

The final, and most simplistic, payback calculation is for scenarios where there is an upfront capital cost and periodic income from the investment. This payback simply calculates the number of years before the investment has reached a break-even point by dividing the upfront capital cost by the yearly earnings. Using these methods the economic feasibility of various scenarios can be determined and compared.

### 2.4 Load Profiles

This section will justify the load profiles to be used within this document. All data is based on actual load profile data from Pacific Gas and Electric Company [30] and summarized using statistical methods shown below [31]. The data will be defined in a 95% confidence interval within upper and lower bound profiles with a time resolution of 30 minutes. It is important to note that the profiles depicted in this section were created using sample data and do not necessarily encompass all load profiles. These are considered to be particular to each system and should be evaluated as such.

The first step to creating these upper and lower bound profiles is to determine the average value point for each 30 minute data point. This is done using .
\[ \bar{Y} = \frac{1}{n} \sum_{i=1}^{n} Y_i \]  \hspace{1cm} (4)

Where

- \( \bar{Y} \)  The average value of the data set
- \( Y_i \)  The data point at index \( i \)
- \( n \)  The number of iterations, or number of data points to be averaged

Next, the standard deviation is calculated using

\[ \sigma_y = \sqrt{\frac{\sum (y - \bar{Y}_y)^2}{n}} \]  \hspace{1cm} (5)

Where

- \( \sigma_y \)  The standard deviation of the data set
- \( y \)  The data point at index \( i \)
- \( \bar{Y}_y \)  The mean value calculated in

Assuming that the distribution at a specific point in time day to day follows a fairly normal distribution, the confidence interval of 95% can be found using

\[ \text{Interval} = \left\{ \bar{Y} - \frac{\sigma}{\sqrt{n}} \ast 1.96, \bar{Y} + \frac{\sigma}{\sqrt{n}} \ast 1.96 \right\} \]  \hspace{1cm} (6)

Applying these equations to residential, small commercial, medium commercial, medium industrial, and large industrial the data the plot of confidence levels combining to make upper and lower bound profiles can be seen in Figure 6-Figure 10, respectively. These plots depict the average profile with a dotted line and the lower and upper bounds around it that 95% of the load demands within the yearlong sample fall within.
Figure 6: Residential Load Profile

Figure 7: Small Commercial Load Profile
Figure 8: Medium Commercial Load Profile
Figure 9: Medium Industrial Load Profile

Figure 10: Large Industrial Load Profile
2.5 The Cost of Electricity

The cost of electricity is an important aspect to understand when investigating economic aspects of distribution. This report will be dealing mainly with the Locational Marginal Price (LMP), which is the price of the next increment of energy at a specific location. This price takes into account the costs associated with the generation, congestion, and losses [32]. Non-profit Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) manage this process of LMP creation under the direction of the Federal Energy Regulatory Commission (FERC). They are the middlemen between the electricity buyers and sellers, collecting and distributing the necessary costs and wages while setting regional market prices [33]. These include the following [34]:

- ISO New England
- New York ISO
- PJM
- Midwest ISO
- Southwest Power Pool
- ERCOT
- California ISO

Using the probabilistic methods laid out in the load profile section of this document, the average, upper, and lower profile from 2012 in the Eastern Massachusetts area can be made with the upper and lower bounds as the edges of the area that contains 99% of the LMP curves for Eastern Massachusetts in 2012, seen in Figure 11 [35]. Therefore, by using an LMP within these bounds, an accurate prediction of what may have been an LMP on any given day in 2012 can be found. These bounds will be used for the price of electricity in the simulation tool for a representative LMP.
This profile will be used throughout the simulations in this document. It will also be assumed that the feeders simulated in any studies performed are such a small percentage of the overall demand of the region that any demand fluctuations on the feeder do not impact LMP greatly enough to change it.

However, the LMP will be changed by the proliferation of electric vehicles over time [36]. This is a function of the percentage of proliferation of electric vehicles, charge timing, EV battery capacities, charger instantaneous demand, and downstream distributed generation or energy storage.
2.6 Large Capacity Energy Storage Systems

This section explores the various energy storage technologies and capabilities. Then a list of benefits energy storage systems can provide a given distribution feeder will be listed and explained. Since there are many conflicting figures available in current literature no future technology specification predictions will be presented.

2.6.1 Energy Storage Technologies

Energy storage technologies are primarily defined by energy density (Wh/kg), power density (W/kg), round-trip efficiency (%), and life time (cycles). The battery technologies that will be compared in this section include lead acid (Pb-Acid), lithium-ion (Li-ion), nickel-cadmium or nickel-metal hydride (NiCd or NiHM), sodium sulfur (NaS) and flow batteries (FBs). These will also be compared with various other technologies including electrochemical double-layer capacitors (EDLCs), pumped hydroelectric, compressed air energy storage (CAES), and steel and composite flywheel technology. A summary of these technologies can be seen in Table 8.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency (%)</th>
<th>Energy Density (Wh/kg)</th>
<th>Power Density (W/kg)</th>
<th>Life (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Acid</td>
<td>70-80</td>
<td>20-35</td>
<td>25</td>
<td>200-2000</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>60-90</td>
<td>40-60</td>
<td>140-180</td>
<td>500-2000</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>50-80</td>
<td>60-80</td>
<td>220</td>
<td>&lt;3000</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>70-85</td>
<td>100-200</td>
<td>360</td>
<td>500-200</td>
</tr>
<tr>
<td>NaS</td>
<td>70</td>
<td>120</td>
<td>120</td>
<td>2000</td>
</tr>
<tr>
<td>EDLC</td>
<td>95</td>
<td>&lt;50</td>
<td>4000</td>
<td>&gt;50000</td>
</tr>
<tr>
<td>Pump Hydro</td>
<td>65-80</td>
<td>0.3</td>
<td>-</td>
<td>&gt; 20 years</td>
</tr>
<tr>
<td>CAES</td>
<td>40-50</td>
<td>10-30</td>
<td>-</td>
<td>&gt; 20 years</td>
</tr>
<tr>
<td>Steel Flywheel</td>
<td>95</td>
<td>5-30</td>
<td>1000</td>
<td>&gt;20000</td>
</tr>
<tr>
<td>Comp. Flywheel</td>
<td>95</td>
<td>&gt;50</td>
<td>5000</td>
<td>&gt;20000</td>
</tr>
<tr>
<td>Flow Battery</td>
<td>40-60</td>
<td>36-45</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 8: Energy storage technologies and their characteristics [37, 38]*
Lead acid is a low cost technology that predates most others and has a reasonable efficiency. Lead is used for the two electrodes and the unit is flooded with sulfuric acid electrolyte. Like many battery technologies overcharging and fully discharging a lead acid battery will damage the battery.

Nickel cadmium and nickel-metal hydride are similar. They have a higher energy density than their predecessor, the lead acid battery. However, they have an increased cost. This technology was seen in early electric vehicles and other high demand applications but was eventually replaced with the superior lithium-ion technology, for the most part.

Lithium-ion has a high energy density. Therefore, it is found in many applications where minimizing size and maximizing use on a single charge is necessary such as cell phones, laptops, and electric vehicles. The downside to this high energy density is cost, lifetime, and power management. The technology is easily damaged by charge rates and over/under charging, so it is important to have a system that ensures the battery is being safely used.

Sodium sulfur batteries use molten sulfur as a positive electrode and molten sodium as a negative electrode. These electrodes are separated from each other by a solid beta alumina ceramic electrolyte. Positive sodium ions flow through this electrolyte to form sodium polysulfide when combining with the sulfur. This technology has a high energy density and is made of low cost materials but must be temperature controlled in order to be in an optimum state.

There are four main flow battery technologies which are zinc bromide (ZnBr), vanadium Redox (VRB), polysulphide bromide (PSB), and zinc-air. The flow battery has separate tanks that hold the two electrolytes. Pumps are used to circulate these two electrolytes into a “flow reactor” where they are separated only by a membrane. This membrane allows the flow of ions, which creates electrical current on the electrodes. These batteries have high energy and power density with a long lifespan. Theoretically they are ideal for large capacity energy storage on the order that is needed for electric distribution. However, development of this technology has proven to be difficult to put into practice and very few units are in service today.

CAES stores energy by compressing air into a storage container. This stored high pressure air can be released at a later time to run a turbine and produce electrical energy. The main drawback of this method is the heat losses incurred when compressing the air. The losses associated with CAES are substantial and makes the efficiency of this system lower than other technologies.
EDLCs hold charge in an electric field by creating a large electrical potential across two separated plates. This technology has the capability of large amounts of power output, but with less energy capacity than most other technologies. EDLCs are smaller in size compared to most other energy storage systems. They are limited in their size because as they grow the electrical potential increases and more electrical insulation is necessary.

Flywheel technology stores energy as rotating inertia. Charging energy is used to increase the speed of a wheel. When energy is needed, the rotating inertia can be used to drive a generator. This technology has fast and high power output capabilities. The main losses in this technology are due to the friction incurred by the wheel while spinning.

2.6.2 Use Cases
The applications of energy storage can be divided into 17 uses cases [39]. They are as follows.

1. **Electric energy time shift** – purchasing energy at an inexpensive LMP period and storing the energy until it can be sold at a higher LMP for an overall profit. This is also called arbitrage. The main factor to be overcome in this case is the efficiency of the battery.

2. **Electric Supply Capacity** – use of storage to offset the investment in new generation to meet demand. However, if the overall day’s energy exceeds the demand this use case does not apply because the energy storage can only store energy, not create it.

3. **Load Following** – using energy storage to maintain a balance in power by increasing or decreasing depending on small time fluctuations in load throughout time. This eliminates the need for generation to cycle with the change in load or for the energy storage to participate in any load following services available in the area.

4. **Area Regulation** – uses energy storage to manage power flow between regulated areas to maintain supply and demand during short time fluctuations.

5. **Electric Supply Reserve Capacity** – uses battery storage as reserve capacity instead of spinning, supplementary, and backup generation.

6. **Voltage support** – energy storage used as a combination of VAR support supplied by the battery’s inverter and “generation” during peak periods to lessen the current demanded through upstream conductors (since higher current yields higher voltage drop through Ohm’s Law)
7. **Transmission Support** – energy storage improves stability, transient voltage drops, and helps to alleviate load shedding due to under-frequencies

8. **Transmission Congestion Relief** – energy storage is discharged during peak periods to alleviate upstream congestion by supplying downstream.

9. **Transmission and Distribution Upgrade Deferral** – when peak demand is nearing feeder capacity energy storage can be implemented to supply power during peak periods that was charged during troughs enabling the upgrade to the feeder to be delayed.

10. **Substation On-site Power** – energy storage is used for power consumption needs within the substation such as switching and control equipment.

11. **Time-of-use Energy Cost Management** – energy storage is used by a utility customer to buy energy during low cost periods and sell during peak periods.

12. **Demand Charge Management** – the energy storage is used by utility customers to discharge during peak periods to reduce the peak demand charge to time-of-use customers

13. **Electric Service Reliability** – the energy storage is used by the utility to provide electricity to customers during outages

14. **Electric Service Power Quality** – the energy storage is used by the utility to ensure that customer’s electric service is within power quality standards

15. **Renewables Energy Time-Shift** – since some renewable produce power during periods of low LMP, the energy storage is used to store the energy produced during periods of low LMP and sold at a higher LMP

16. **Renewables Capacity Firming** – the energy storage is used to decrease the fluctuation in the output of renewable sources to increase their overall capacity factor

17. **Renewable Generation Grid Integration** – renewable generation has negative impacts on the grid, such as slow transients and islanding. Energy storage can be used to mitigate these effects.

These use cases are usually put into five categories, as seen in Table 9.

<table>
<thead>
<tr>
<th>Category</th>
<th>Use Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Supply</td>
<td>1 and 2</td>
</tr>
<tr>
<td>Ancillary Services</td>
<td>3-6</td>
</tr>
<tr>
<td>Grid System</td>
<td>7-10</td>
</tr>
<tr>
<td>End User/Utility Customer</td>
<td>11-14</td>
</tr>
<tr>
<td>Renewable Integration</td>
<td>15-17</td>
</tr>
</tbody>
</table>
Many of these use cases are difficult to justify monetarily. Therefore, a combination of uses cases is expected to produce the maximum benefit for energy storage. In this research the main use cases that will be investigated are electrical energy time shift, electric supply capacity, voltage support, time-of-use energy cost management, demand charge management, electric service reliability, renewables energy time-shift, renewables capacity firming, and renewables generation grid integration.
3 Development of the Modeling System

This section provides an in depth explanation of the workings of the simulation environment that was built in Matlab’s Simulink. The model is capable of simulating three-phase single branch feeders in any configuration. The configuration of the model can be easily altered by adding, removing, and rearranging blocks associated with components that make up a feeder. The blocks included in the modeling system are the substation, lines, loads, generation, battery energy storage systems (BESSs), capacitors, and transformers. The user is able to input all load and/or generation curves for each load or generation component of the model, an LMP curve, an SREC price, impedance values for all cables, transformer characteristics, and capacitance values.

The system can simulate the feeder’s performance for any specified duration ranging from seconds to months. When simulating the feeder performance voltage, current, and power quantities are calculated at each block for the specified time duration. Therefore, the electrical behavior at any point on the feeder can be investigated. The model also calculates the cost of energy supplied to the system and total income from SRECs. Therefore, the model can be used to both electrically and economically study feeder configurations.

The model works to balance the power from the substation to the consumed power in the rest of the model in a control loop concept rather than a conventional matrix system solution. The substation block delivers a specified amount of power to the first feeder block, the power demanded or supplied by that block is added or subtracted and remaining power passed to the next block. The final block of the model is the end block. There will be power at the end block if there is a difference between the amount of power produced by the substation and the consumed power by the feeder blocks. In this case the substation dispatches a new power value at the next time step that has been adjusted by the amount of residual power at the end block from the previous time step. See Figure 12 for a graphical depiction of this signal flow approach. Therefore, the substation is always working to settle on a steady-state power output value. This means, as long as the power demands are changing, there will be some inherent error. But, with small time steps, the amount of error can be kept arbitrarily low and accuracy high.

From a signal analysis view, values of complex power and voltage are passed from block to block iteratively at a defined time step to simulate durations of time. There are a total of twelve signals are transmitted between blocks. Each phase has four signals associated with it which represent the real and
imaginary values of for voltage and power. At the end of the feeder the value of any residual power is transmitted back to the substation so it can be compensated for in the next iteration of the simulation.

### 3.1 Substation and End Blocks

The substation block is responsible for dispatching the correct amount of power into the model and setting the system voltage. It receives signals from the end block representing residual complex power. This residual power represents the difference in feeder demand and the amount of power the substation dispatched in that particular time step. This value is added to the previous time step's power dispatch quantity to determine the next quantity of power to be dispatched from the substation. A diagram of this concept can be seen in Figure 12 where the feeder model consists of all the particular blocks that are pertinent to that particular feeder (line impedances, capacitors, generation, loads, etc.).

![Figure 12: Model Signal Flow](image)

Due to the nature of the feedback system differentiation, integration, and proportional gain are included in the feedback loop for conventional control theory application. The differentiation determines the current rate of change of the residual and can therefore be used to help the model better predict the system behavior. Integration removes error over time to ensure convergence. The gain can be used to control the sensitivity the model has to the residual values. The model takes the constants that determine the amount of gain and differentiation. These constants are altered by double clicking on the substation block and entering the values in the corresponding fields. An equation defining this operation can be seen below.
where

\[ u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dx} e(t) \]

\( u \)  Amount of change to be applied to previous time step value
\( K_p \)  Proportional gain constant
\( K_d \)  Derivative constant
\( K_i \)  Integral constant
\( e \)  Error (Residual from end block)

These values should be tuned per model to ensure the greatest accuracy. Figure 13 shows an ideal response of the model. Figure 14 shows the actual output of the model when well-tuned to have an insignificant amount of error. It should be noted that the voltage signals do not require differentiation, gain, or memory (from previous time step) because they are not a function of their end of the feeder residual.

The user can define the phase voltages and angles as well as the equivalent impedance of the substation in ohms at the substation conveniently in a prompt, shown in Figure 15.
This prompt is accessed by simply double clicking the substation block in the simulation environment. The end block has no such prompt because it serves solely to transmit the residual power values back to the substation block.

### 3.2 Line Block

The line block is responsible for implementing voltage and power drops associated with lines or cables. The power and voltage enter the block, are altered to reflect the losses of the impedance values, and their new values are output. This signal flow can be seen in Figure 16.
The impedance value is a static value that is input by the user in units of ohms in a similar prompt to that of the substation block. The prompt for this block can be seen in Figure 17.

The current is calculated using

\[ I = \frac{S^*}{V^*} \]  

(7)
\[ V_{\text{out}} = V_{\text{in}} - IZ \]  \hfill (8)

The power consumed by the impedance is then calculated using and.

\[ P_{\text{loss}} = \frac{|V_{\text{in}}|^2}{R} \]  \hfill (9)

\[ Q_{\text{loss}} = \frac{|V_{\text{in}}|^2}{X} \]  \hfill (10)

These quantities can then be subtracted from the input signals to determine the necessary output values.

### 3.3 Transformer Block

The transformer block is responsible for stepping voltages up or down throughout the feeder. The user must supply the turns ratio, volt-ampere rating, and the real and reactive impedance quantities in per unit. Per unit values are used for the input because they are predominantly what is displayed on transformer specifications. In the simulation block, these per unit values are turned into actual impedances using and [40].

\[ R_{TR} = \frac{1}{100} \left[ \frac{(\%R)(Secondary \ line \ voltage)^2}{\text{Transformer \ voltampere \ rating}} \right] \]  \hfill (11)

\[ X_{TR} = \frac{1}{100} \left[ \frac{(\%X)(Secondary \ line \ voltage)^2}{\text{Transformer \ voltampere \ rating}} \right] \]  \hfill (12)

In the event that a single impedance is given in place of the resistive and reactive per unit impedances, the necessary values can be calculated and still used in the previous equations by using the following equations.
\[ \theta = \tan^{-1}\left(\frac{X}{R}\right) \]  

(13)

\[ \%R_{TR} = \%Z_{TR} \cos \theta \]  

(14)

\[ \%X_{TR} = \%Z_{TR} \sin \theta \]  

(15)

First the impedance angle is found by taking the arctangent of the X/R ratio in Equation 13. Then multiplying the percent impedance by cosine or sine of this angle will produce the individual resistive and reactive quantities in Equations 14 or 15.

Figure 18: Transformer Parameter Prompt

The prompt can be seen in FIG. This is accessed by double clicking the transformer block inside the simulation environment.
3.4 Generation/Load Block

The generation and load block are similar in nature. These blocks produce or consume power in the model at as defined by the user to represent generation or load variation vs. time. As time progresses the corresponding power is either added or subtracted to the signal flow. This signal flow is seen in Figure 19.

![Load/Generation Block Signal Flow Diagram](image)

Figure 19: Load/Generation Block Signal Flow Diagram

The load/generation and power factor values are input in list form and intermediary values are interpolated. These can be accessed by double clicking the load curves within the block. These curves feed into MATLAB functions which perform the necessary complex math to split the values into real and imaginary values. The values are then either added (generation) or subtracted (load) to the input signals of the block to determine the new output.

3.5 Capacitor Block

Capacitors are often used in distribution feeders to raise the voltage level. The capacitor creates a leading current that, when passed through inductive components, causes a voltage swell. Since this simulation environment passes reactive power as a signal value, the capacitor block simply add its user defined value kvar value to its input signal from the model to determine its output. The only user input for this block is the kvar rating of the capacitor.
3.6 Battery Energy Storage System Block

The BESS block can operate using different algorithms. The algorithms included in the model are optimum energy-time shift, maximum peak-shaving, generation smoothing, and stability enhancement. The operations of these algorithms are outlined in Chapter 4 of this thesis. However, the user may also input a custom algorithm into the BESS block to achieve any other functionality. The algorithm can be used to control the output of the BESS, but the BESS will not perform any action outside its specified operational limits. In the case that the user defined algorithm requests the BESS to perform outside its specified limits, the BESS will perform to the best of its abilities. For example, if the BESS was defined to have a maximum power output of 500kW with a 1MWh capacity and the user defined algorithm requests an output of 750kW for three hours, the BESS will output its maximum power output of 500kW for two hours.

The battery energy storage system BESS block is able to take in energy and at a later time to output energy. The output energy is equal to the input energy multiplied with the round trip efficiency, which represents inverter and chemical losses. The battery takes in numerous user defined parameters, seen in Figure 20.

![Figure 20: Battery Energy Storage System Parameter Prompt]
The battery obeys the internal control block that houses the various algorithms discussed previously to determine when to charge or discharge. The control block’s output is a request of the battery. It may send a signal telling the BESS to charge or discharge. However, the BESS’s state is kept track of and not allowed to go outside the operational limits defined by the user. This signal view approach is seen in Figure 21.

![Figure 21: Battery Energy Storage System Block Signal Flow Diagram](image)

The BESS then adds or subtracts the necessary power to the line to be passed on to the next block in the simulation.

### 3.7 Economic Calculations

Basic economic calculations are handled in the “Reporting” block in the modeling environment. This block takes the input of the LMP curve and Renewable Energy Credit (REC) price per MWh. A REC is a credit given to producers of renewable energy by the appropriate governing authority in the area of the generation. This REC can be sold to companies that want to or are required to have a portion of their electrical demand be supplied by renewable sources. Therefore, the selling price of RECs was included in the economic calculations. To determine the price of electricity at a particular time, the energy that is used by the feeder is multiplied by the programmed LMP at that same time and summed at the end of the simulation to determine the worth of the consumed energy. These can then be summed and divided according to the time step, duration of simulation, and desired energy unit to determine the overall cost. Any energy produced by solar energy is also multiplied by the user defined value of RECs.
These basic economic calculations were included in the model because they are useful in almost all economic studies. However, all relevant information is exported to MATLAB for further analysis. Economic optimization techniques can be used by making use of this exported data to analyze the most recent simulation, make adjustments, and re-run the simulation to converge on an optimum scenario. These optimization tools are discussed in a later section.
4 BESS Algorithms

This section describes four BESS charge/discharge algorithms that will be used during analysis in future chapters. There are several different optimizations that can be desirable when determining BESS charge/discharge schedules. The following algorithms will address optimum economic operation, maximum smoothing, maximum peak shaving, and increasing generation stability.

4.1 Dynamic Programming for Optimum Economic Operation

Dynamic programming can be used to find the optimum path through a directed graph, whether the optimum for the given problem in a maximum or a minimum. A directed graph consists of nodes and directional edges, as seen in Figure 22.

![Figure 22: Simple Map](image)

The directional edges are the arrows connecting the nodes, which denote direction and value, the value being denoted by the number on the edge. The nodes are the points at which the edges are connected and are denoted using capital letters within the circles. The nodes A and I indicate the starting and ending points, respectively. Consequently, the path must start at node A and traverse the graph to adjacent nodes in the directions connected an edge arrow until reaching node I. The summation of the values of each edge traversed from node A to I indicates the value that would be achieved by seeking that particular path through the graph. By inspection, it can be seen that there are various path options that can be taken with total cumulative value varying with each path option. In the particular graph shown above the decisions are denoted by the D1, D2, D3 and D4, which lie between adjacent groups of vertical nodes.
The method of dynamic programming works backwards, in this case, from the end of the graph (node I) to the start (node A) to determine the optimum path. Each node has an optimum path from itself to the end of the graph. Working from the end of the graph (node I), the first edge option is seen under D4. Since the edges traversing D4 connect directly to the end node, it can be deduced that these edges will be the optimum path for each node one step away from the end node. In other words, being one step away from the end node, there is only one possible decision that can be made to connect to the end node, making it the optimum. Next, the analysis will move to the node(s) one more step away from the end of the graph (two steps from the end node). This area is denoted D3. Each edge value to adjacent node(s) in the direction of the end node will be added to the optimum path of the node it connects to, determining the optimum path from the node two steps away to the end node. These values can be compared and the highest or lowest path direction will be chosen to be the optimum depending on whether the desired outcome is to maximize or minimize the path value. Iterating this process for all decisions in the graph, regardless of size, and for each node will produce the final optimum direction from the start node of a graph given the same information. Finally, by following this optimum direction at the start node and each subsequent optimum direction, the optimum path through the graph can be determined. The end result will yield a graph with the optimum path direction and value at each node known, as seen in Figure 23.

![Figure 23: Labeled Simple Map](image)

In this example, the maximum path value is desired. It can be seen that the last decision to be made is D4 and the path options for D4 stem from G and H to the end node, I. Since this is the first iteration, there is only one option for each node (G and H), which is to go to node I. Therefore, the optimum path from either node G or H is to move to Node I, which is summarized in Table 10.
Table 10: Decision Table for D4

<table>
<thead>
<tr>
<th>D4</th>
<th>Edge Value to Node</th>
<th>Edge Value + Previous Best</th>
<th>Forward Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>G</td>
<td>2</td>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>3</td>
<td>I</td>
</tr>
</tbody>
</table>

The next decision, working backwards, is decision three (denoted by D3). The nodes that have edges traversing toward the end of the graph in D3 are D, E, and F. Each edge value is added to the previously calculated optimum path of the node it connects to (in Table I) to determine the corresponding path values if that direction were to be taken. Once all options are gathered, the highest yielding path direction is chosen. The outline of their decisions can be seen in Table 11.

Table 11: Decision Table for D3

<table>
<thead>
<tr>
<th>D3</th>
<th>Edge Value to Node</th>
<th>Edge Value + Previous Best</th>
<th>Forward Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G</td>
<td>6</td>
<td>G</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>5</td>
<td>H</td>
</tr>
<tr>
<td>G</td>
<td>6</td>
<td>N/A</td>
<td>G</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>E</td>
<td>N/A</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

It can be seen that the edge values between the adjacent node and the options are found (seen in the “Edge Value to Node” column). These values are added to the values of the best path of each option node, which was reported in the previous decision’s table’s “Edge Value + Previous Best” in the row corresponding to the node option. This value is then reported in the current decision’s “Edge Value + Previous Best” column for the corresponding node being left from. Nodes that do not have an edge connecting them are marked “N/A” and not taken into account. The decision is then made depending on which node yields the highest or lowest sum of values and is reported in the last column. In this example, the goal is the maximum path value, so the maximum value is used. The second decision (D2) is seen in Table 12 and the same process that was used for D3 is used.
Table 12: Decision Table for D2

<table>
<thead>
<tr>
<th></th>
<th>Edge Value to Node</th>
<th>Edge Value + Previous Best</th>
<th>Forward Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>E</td>
<td>F</td>
<td>D</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>C</td>
<td>N/A</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

The last step shows the initial direction of the path from the start node (node A). This is seen in Table 13 having only two edges and one node to leave from in the direction toward the end of the graph (node I).

Table 13: Decision Table for D1

<table>
<thead>
<tr>
<th></th>
<th>Edge Value to Node</th>
<th>Edge Value + Previous Best</th>
<th>Forward Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>C</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>4</td>
<td>14</td>
</tr>
</tbody>
</table>

It is seen that the optimum initial direction is to move from node A is to node C and the path value will be 15 units. Table 13 reports that the optimum path from node C is to move to go to node E. The third decision table demonstrations that the optimum direction from node E is to node H. Finally node H must traverse to node I. Therefore, the overall path is found to be C-E-H-I for a total value of 15 units.

The method of dynamic programming can be applied to BESS charge/discharge to find the optimum output vs. time. A graph similar to the one seen in Figure 24 will represent the path of the BESS input/output.
Each black dot represents a node and the arrows represent the edges. The edge’s slopes indicate the rate of charge (positive slope), discharge (negative slope), or charge hold (slope of zero). It is assumed that if the BESS holds a constant charge there is a negligible amount of loss due to the short duration of time before next operation. If the edges traverse the graph with positive slope, then the BESS is acquiring charge. Therefore, the nodes are representative of charge as well. It can be seen that the nodes, in this case, are increasing by 0.5MWh. It can also be seen that the BESS’s maximum capacity is set at 2MWh. This gives the graph a pyramid characteristic with the top cut off at the BESS capacity.

The edge values corresponding to the BESS operation can be calculated to a dollar amount by multiplying the rate of change by the regional instantaneous LMP. Since the operation of the BESS impacts load on the feeder, the costs associated with these changes must also be taken into account. Therefore, the instantaneous load value with the BESS as an addition (charging) or subtraction (discharging) can be multiplied by the instantaneous LMP and be applied to the edge values.

Therefore, the optimum path from the left most node (time zero) to the right most node (ending time of duration under investigation) will be representative of the cost of the various options of the feeder given different BESS operation. Using the previously described method of dynamic programming, the optimum path through the graph represents the optimum charge/discharge of the BESS vs. time. The algorithm can become increasingly accurate by decreasing the time step (distance between nodes horizontally on a time scale) and increasing the options of rate of change between nodes (creating more edge values coming from each node).
4.2 Power Flow Smoothing

Due to the variable nature of renewable generation, it can be desirable to want to smooth out the power production from these units for feeder reliability and predictability. However, the short term variations in power production from renewable sources are nearly impossible to predict. Therefore, an algorithm for smoothing this renewable power production must do so without using any predicted values. This section will describe one method of doing so.

This algorithm will attempt to limit the rate of change by supplying energy during energy production dips and consuming energy (charging) during the energy peaks within the capability of the BESS. The summation of these powers will then be transmitted to the grid, as seen in Figure 25. It may also be helpful to see a broad flowchart overview before investigating details of the algorithm, this is seen in Figure 26.

![Figure 25: Smoothing Algorithm Block Diagram](image)
Figure 26: Smoothing Algorithm Flowchart
The symbols that will be used to describe this algorithm are seen in Table 14.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{max}$</td>
<td>Maximum rate of change allowed at net meter (user specified)</td>
</tr>
<tr>
<td>$R_{BESS}$</td>
<td>Maximum rate of change BESS inverter can produce</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Time step</td>
</tr>
<tr>
<td>$p_{battMax}$</td>
<td>Maximum BESS power output rating</td>
</tr>
<tr>
<td>$p_{batt0}$</td>
<td>BESS power output for time t-1</td>
</tr>
<tr>
<td>$p_{batt1}$</td>
<td>BESS power output for current time</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Net meter power output for time t-1</td>
</tr>
<tr>
<td>$p_1$</td>
<td>Net meter power output for current time</td>
</tr>
<tr>
<td>$p_{solar0}$</td>
<td>Solar power output for time t-1</td>
</tr>
<tr>
<td>$p_{solar1}$</td>
<td>Solar power output for current time</td>
</tr>
<tr>
<td>$SOC_{Max}$</td>
<td>Maximum BESS charge capacity</td>
</tr>
<tr>
<td>$SOC_1$</td>
<td>BESS charge at current time</td>
</tr>
<tr>
<td>$SOC_2$</td>
<td>BESS charge at time t+1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>BESS round-trip efficiency</td>
</tr>
</tbody>
</table>

It is assumed that the converter technology of the BESS can tolerate near instantaneous variation of output value. The first step is to determine whether the renewable generation is increasing or decreasing production at a rate higher than desired.

\[
\text{abs} \left( \frac{p_{solar1} - p_0}{\Delta t} \right) > R_{max}
\] (16)
If this is true, then the BESS should step in and do what it can to limit this quick change in energy so it is not passed onto the grid. If this statement is not true, then the algorithm does not need to operate. In the case that it is true, it must be decided if the rate of change is in the positive or negative direction because the BESS will handle the situations differently. We will investigate the situation where the rate of change is positive first.

\[
\left( \frac{P_{\text{solar}} - P_0}{\Delta t} \right) > 0
\]

(17)

Once we have determined the rate of change is positive, we must determine how much the BESS can help to reduce the rate of change, if at all. Therefore, the BESS can either consume enough power to bring the rate of change to the acceptable limit \( R_{\text{BESS}} = R_{\text{Max}} \), or it cannot consume enough power to completely alleviate the situation and can only help within its physical limits. We will first look at the situation where the BESS can consume enough energy to completely limit the rate of change.

\[
\left( P_{\text{solar}} - (P_0 + R_{\text{max}}\Delta t) \right) < \left( P_{\text{batt},\text{Max}} - P_{\text{batt},0} \right)
\]

(18)

It is seen that the optimum operation point is calculated as the previous point of operation added with the desired rate of change \( P_0 + R_{\text{max}}\Delta t \) and represents the desired operating point. Since it has previously been determined that the renewable power production rate of change is positive, it is known that this point lies above the desired operating point. Therefore, the subtraction of the desired operating point from the output of the current renewable power production represents the amount of power the BESS must consume in order to limit the rate of change to the specified value \( R_{\text{max}} \). This can be seen graphically in Figure 27.
On the right the amount of power consumption available in the BESS is calculated. Finally, it must be determined whether or not the BESS can consume the amount of power necessary to perform this for the duration of one time step (Δt). We will first look at the situation where it can consume enough energy.

\[ SOC_1 + \beta(p_{solar_1} - abs(p_{batt_0} + R_{max}\Delta t)\Delta t) \leq SOC_{MAX} \]  \hspace{1cm} (19)

It can be seen in Equation 19 that the current state of charge is being added to on the left hand side. The current state of charge is used because the algorithm is determining whether the state of charge at the next time step will be within the BESS’s capabilities. Therefore, this current state of charge is then added to a term that is multiplied by the round trip efficiency of the BESS representing the energy that will be consumed in one time step. This is done because the efficiency of the BESS is taken into account during the charging. The amount of energy to be charged is amount of power needed to limit the power to meet the desired rate of change (much like Equation 18). In this case the BESS output would be calculated using Equation 20 and the next state of charge in Equation 21.

\[ p_{batt_1} = -(p_{solar_1} - (p_0 + R_{max}\Delta t)) \]  \hspace{1cm} (20)
\[ SOC_2 = SOC_1 + \beta (\text{abs}(p_{\text{batt}}) \Delta t) \] (21)

It can be seen in Equation 20 that the amount of power consumption necessary to make up the difference to achieve the maximum rate of change. The next state of charge is calculated simply by adding the amount of energy the BESS will be consuming taking efficiency losses into account. If the BESS is too close to its maximum state of charge it would not be able to consume the energy necessary to limit the rate of change.

\[ SOC_1 + \beta (p_{\text{solar}} - \text{abs}(p_{\text{batt}} + R_{\text{max}} \Delta t) \Delta t) > SOC_{\text{MAX}} \] (22)

In this case the BESS would not consume any energy and will lay dormant. There may be some available capacity for the BESS to charge, but if the time step is small enough this energy is assumed to be negligible and that the BESS is effectively at its maximum charge capacity. Equation 23 depicts the BESS not having enough capacity to consume the power necessary to limit the rate of change of power in the system.

\[ (p_{\text{solar}} - (p_0 + R_{\text{max}} \Delta t)) \geq (p_{\text{batt, max}} - p_{\text{batt}}) \] (23)

In this case, the BESS will do the best it can to help alleviate the situation, but it will not be able to limit the rate of change to the desired value. Similar to the case where the BESS could consume enough power to completely alleviate the situation, the algorithm must test to ensure the BESS has enough energy capacity to use the BESS’s available power capacity for the period of a time step.

\[ SOC_1 + \beta (\text{abs}(p_{\text{batt, max}}) \Delta t) \leq SOC_{\text{MAX}} \] (24)

In Equation 25 it can be seen that the state of charge is calculated using the maximum BESS allowable output. Since this operation is consuming energy, the state of charge will increase. In the event of this state the BESS output will be governed by Equation 26 and the SOC at the next time step by

\[ p_{\text{batt}} = -p_{\text{batt, max}} \] (25)
If the algorithm determines that the BESS does not have enough energy capacity to consume any energy (inverse of Equation 24), the output from the BESS will be zero and the state of charge will remain constant. This concludes the options the algorithm has to make pertaining to when the value of the rate of change in renewable energy power is positive and greater than the desired rate. However, we must investigate when the rate of change is negative and greater than the desired rate.

\[
\left( \frac{p_{solar_1} - p_0}{\Delta t} \right) < 0
\]  

(27)

Similarly to when the rate of change is positive, there will be the options pertaining to amount of available power and then, subsequently, available energy. However, unlike the options while the rate of change was positive, the power will now be supplied by the BESS to offset the negative swing instead of consumed to offset a positive swing. The first option that will be considered will be whether or not the BESS has enough available power to limit the renewable power production change to the desired limit.

\[
\left( p_0 - R_{max} \Delta t \right) - p_{solar_1} < \left( p_{batt_\text{max}} - p_{batt_0} \right)
\]  

(28)

In it is shown that the BESS can supply enough power to limit the rate of change to the desired values. It can be seen that the desired point of operation is the previous point of operation minus the desired rate of change. Since it is known that the renewable power production is a point below this, subtracting this first term from the renewable production will yield the amount of power the BESS needs to compensate to attain the desired operating point. This can be seen graphically in
It now must be determined if the BESS has enough energy to supply this power for the duration of a time step.

\[ SOC_1 - \beta \left( \text{abs} \left( (p_0 - R_{\text{max}}\Delta t) - p_{\text{solar}_1} \right) \Delta t \right) \geq 0 \]  \hspace{1cm} \text{(29)}

It can be seen in \text{Equation} 29 that the amount of energy necessary is subtracted from the current state of charge to determine what the state of charge at the next time step will be. In this case, it is tested to be greater than or equal to zero, meaning there is enough energy in the BESS to supply the desired power for the duration of a time step and possibly additional energy stored. In this case the BESS will output the amount of power necessary to bring the system to the point of desired operation and limit the rate of power rate of change. The BESS output and state of charge calculations for this scenario can be seen in \text{Equation} 30 and \text{Equation} 31.

\[ p_{\text{batt}_1} = (p_0 - R_{\text{max}}\Delta t) - p_{\text{solar}_1} \]  \hspace{1cm} \text{(30)}

\[ SOC_2 = SOC_1 - \beta \left( \text{abs} \left( p_{\text{batt}_1} \right) \Delta t \right) \]  \hspace{1cm} \text{(31)}
It can be seen that unlike the case where the rate of renewable power change was positive, this state of charge calculation is subtracting energy from the BESS because it is now offsetting a negative swing and is therefore producing power instead of consuming it. Similarly throughout all cases, if it is found that the BESS cannot supply (or consume) enough energy for the given scenario (inverse of ), the BESS does not supply or consume and the state of charge remains constant.

The last possible state the algorithm can encounter is when the absolute value of the slope is greater than the desired value, the slope is negative, and the BESS cannot supply all the power necessary to achieve the optimum operating point.

\[
(p_0 - R_{max} \Delta t) - p_{solar} \geq (p_{batt\_max} - p_{batt\_0})
\]  

(32)

It can be seen that in the opposite of In this case, the BESS cannot supply enough power to achieve the optimum operating point, but it may be able to bring it closer to this point. In this case the BESS will be outputting its maximum and the state of charge will be decreasing by this power output over a time step (seen in and ).

\[
p_{batt\_t} = p_{batt\_max}
\]  

(33)

\[
SOC_2 = SOC_1 - \beta(\text{abs}(p_{batt\_t}) \Delta t)
\]  

(34)

4.3 Peak Shaving

In this scenario the BESS attempts to limit the maximum fifteen minute demand value of a facility for a month. It is assumed that the owner of the BESS is the facility and that there is a good understanding of the daily load profile. With this load profile prediction, it is possible to calculate the amount of the peak demand that can be shaved by discharging the BESS during the peak demand period. In order to have the available energy in the BESS to discharge during the peak period, the BESS must be previously charged. Therefore, the same method outlined in this section can be used to determine the demand minimum that precedes the demand maximum and charge during this time. If the charge time interferes with the discharge time, it is moved further back in time. If it the charge time
cannot be moved any further back in time, the amount of possible charge limits the amount of peak shaving.

This algorithm works by using the known capacity of the BESS (efficiency is taken into account during the charging of the BESS). The peak value of the day is then found. Two points from this peak are moved throughout iteration from this peak point away from each other. These two points are used as the limits of integration. This integration will be subtracted from the initial constant value point to isolate only the discharge area of the BESS. Therefore the integration for the discharge area can be found in EQN and shown in FIG.

\[
BESS \text{ Discharge Area} = \int_{x_1}^{x_2} (lp(x) - lp(x_2)) \, dx = BESS \text{ Capacity}
\]

The notation uses \(x_2\) to denote the demand value for the constant value, but both demand values for \(x_1\) and \(x_2\) are equal and can be interchanged. Since the value of the integration is already know to be the capacity of the BESS less the efficiency, the values that are actually important from this iterative process is the limits of integration to achieve this known value. Therefore, when the value output of the integration matches that of the known value, the limits of integration can be used as the values to start and stop the discharging of the BESS.

The amount of power that the BESS should be discharging at any moment within the found limits is simply the demand value at the current time less the demand value at the starting (and equally ending) found limit. This will ensure that the peak is capped by the BESS and there is no chance of the peak occurring before or after the BESS operation.
For multiple peaks a second, third, etc. integration is created in a similar fashion to EQN. The amount of peak shaving the BESS can handle is then determined when the sum of all integrations equals the known quantity of BESS energy availability. We are then left with a series of pairs of intervals when the BESS should be discharging. The amount of power to discharge is also calculated in the same fashion as the singular case.

\[ BESS \text{ Discharge Areas} = \int_{x_1}^{x_2} (lp(x) - lp(x_2)) \, dx + \int_{x_3}^{x_4} (lp(x) - lp(x_2)) \, dx = BESS \text{ Capacity} \]

These same methods for discharging can be used to find the minimum loading area to charge the BESS during. The key difference between the two methods is that the iterations will stop at the energy value equated to the sum of the BESS capacity and losses. Therefore, the charging area will be larger than the discharge area.

5 Stability Enhancement

With the penetration of technologies such as smart grid remote monitoring and switching, distributed generation, and Battery Energy Storage Systems (BESSs), making use of microgrids is becoming a feasible option. Microgrids that are or can be operated independently from a large scale electrical grid can be useful to enhance overall reliability to fringe customers by allowing the detachment from the larger power grid when necessary. However, while the microgrid is operating in isolation from the main power grid stability becomes an issue if a fault were to occur within the system.
This stability issue is due to the lack of generation options and mechanical inertia available in the smaller system.

Every microgrid needs a form of controllable generation to ensure that power needs are met while islanded. The sizing of this generator or generators depends on the amount of loading and the desired safety margin. By using a BESS as a load directly after a fault, the generator governor can be given additional time to adjust to the new necessary output. Previously, if a fault was cleared within an acceptable time but the reconnected demand was much smaller than the pre-fault value, the generator would be in danger of reaching an unstable condition.

Figure 29 depicts the load curves where pre-fault mechanical power is greater than any operation point on the post-fault power-angle curve. It is shown that the mechanical power must be lowered to a point where this is true. However, this adjustment takes time and if it is not quick enough can result in instability. Therefore, if the BESS is used as a variable load that decreases at the same rate the generation mechanical power decreases the situation will remain stable. This also allows the generator to run closer to its maximum output due to the decreased necessity for a large safety margin, allowing a smaller generator to be used and therefore lowers capital costs.

![Figure 29: Faulted Load Curves](image-url)
In order for this system to work properly the generator and BESS must be connected to the same bus and therefore see the same fault clearing time. This holds true for all possible types of feeder configurations to guarantee the BESS can support the generator.

As an added benefit, the BESS can be used to time-shift energy to optimize the fueling costs of the generation during steady-state operation and make use of energy from renewable generation during high demand periods. Since fuel to the controllable generation is the primary cost of running the isolated microgrid, this optimization can be financially beneficial. To study this optimization a modeling environment that uses daily/monthly/yearly production and demand curves is used with a discrete optimization technique. Combining the benefits of using the BESS for stability enhancement and for economic benefit shows the BESS as a key factor in successfully operating an islanded microgrid in steady-state and transient periods.

It is assumed that the microgrid being studied has voltage control equipment that acts when load is shed. It will also be assumed that a round rotor machine will be used and therefore have the swing equation shown in Equation 35.

\[
\frac{H}{\pi f_0} \frac{d^2 \delta}{dt^2} = P_m - P_e
\]  

(35)

In traditional stability analysis the mechanical power is held constant while electrical power changes with fault status. However, in some cases the post-fault electrical power is below the pre-fault mechanical input power and therefore has no intersection points. The results for this scenario are seen in Chapter 7.
6 Test Feeder Configuration

This section defines the base test feeder configuration that will be used to study various scenarios. A simplified feeder configuration will be used comprising of a substation (infinite bus), two loads, and the renewable generation and BESS. The two loads are located on either side of the renewable generation and BESS connection representing the cumulative of the loads on an actual feeder. This allows for drastic simplification of feeder configuration and can be seen in Figure 30.

By changing the values of Z1 (infinite bus impedance), Z2, Z3, Load 1, and Load 2 a vast array of feeders can be implemented as well as making use of convenient ratios such as Load 1/Load 2 (using peak values to quantify standard load profiles) and Z2/Z3 to make broader conclusions.

This configuration will also be useful for simulation iterations that require a block to be moved throughout the feeder for optimal placement. This can be done by moving impedance from one side of the block to the other for the desired range. With the impedance usually defined in ohms per 1000 meters by the manufacturer, this can be translated to miles easily. Therefore, by iterating through these calculations, an optimum position can be found using automation instead of numerous simulations set up by hand.
7 Results and Analysis

This chapter outlines simulation results for a system comprised of residential loads with EV charging, distributed generation, and energy storage in all possible combinations. The methods will be used to determine electrical and/or economic optimum operation points for feeders with various installed technologies. All work will be done on an example feeder to show how the studies can be carried out using the simulation environment described in Section 3.

All results are obtained using the feeder configuration described in section 6; however technologies such as renewable generation, BESS, and EV will be included in the cases when necessary. This section will use examples to attain results for analysis; however in practicality each case is different. Therefore, this section is meant to display how the simulation model discussed in this document can be used effectively to study various technologies’ effects on the electrical grid.

A base case will first be investigated to act as a control, and then a single technology will be added to the system and optimized either electrically or economically. These technologies will then be paired, and finally grouped to determine their relative impacts upon one another. All results were attained by iterating multiple simulations in the simulation environment described in Section 3.
7.1 Base Case

The base case will serve as the control for the various other systems that will be studied. In this case a hypothetical seven mile 13.8 kV feeder with residential winter weekday loading (seen in section 2.4) and a simplified grouped configuration (seen in section 6) will be used. Standard values of impedance measured in ohms per 1,000 meters were used to achieve the feeder length and a peak load of approximately 6 MW was assumed. The load and voltage profile for a twenty-four hour period can be seen in Figure 31.

![Base Feeder Configuration](image)

**Figure 31: Base Case Load and Voltage Profile**

To achieve acceptable minimum voltage levels, 1750 kvar of capacitance is installed at the beginning and end of the line. It can be seen that the voltage is well within ±5% per unit of nominal. Therefore, it can be seen that the base case is well within voltage limits. However, it will be assumed that the cable can carry a maximum of 250A per phase. Therefore, if the total three-phase current through the cable at any point reaches 700A continuous or above, the cable is in danger of overheating and failure. At the base case, the maximum current seen is 450A three-phase, or 64% capacity.
7.2 Electric Vehicle Penetration

Electric vehicle penetration will most affect the residential areas due to the nature of their ownership. EV charging also occurs during the peak of residential demand for similar reasons. Therefore, the purely residential profile chosen for this study represents the worst case scenario for EV penetration, and also the most probable (seen in Section 2.4). EV charging is distributed evenly throughout loads one and two of the base case feeder.

The main concern of adding EV (without any other technologies) to a feeder is at what amount of penetration the EVs will the feeder be overloaded. This comes at a point when the peak demand is high enough to overload the cable’s ampacity. It is assumed that EV charging in a residential area is done when residents return to their homes from work at night. For this study a random distribution of charging start times and charge profiles from Section 2.1.2 were summed to create a standard load profile of EV charging. The total amount of EV load was added evenly to loads 1 and two of the test feeder configuration seen in 6 in small increments with the maximum amperage through the feeder recorded at each step. A depiction of steps of additional EV on a residential load curve can be seen Figure 32.

![Figure 32: Increasing EV Penetration on Residential Load Profile](image)
By iterating the addition of the EV load and determining maximum cable current at each step during the peak load periods, a plot of maximum cable current vs. EV load can be created. This plot depicts how much an increase in EV load will affect the loading of the feeder cable. It can be seen by inspection of Figure 32 that the addition of EV load falls on the peak load demand and will therefore directly impact the maximum loading of the cable. The resultant maximum current vs the percentage of load that is EV can be seen in Figure 33.

![Maximum Allowable EV Penetration](image_url)

Figure 33: Maximum Allowable EV Penetration

A cable’s amapcity rating varies depending on the type of cable and environmental aspects. For example’s sake, the cable in this system is assumed to have a capacity of 700A continuously. It can be seen that if the example system were to have its load comprised of more than approximately 58% EV the maximum current seen would be higher than the rating of the cable. Therefore, approximately 58% of the total residential load is the maximum allowable percentage of EV penetration this particular example feeder can handle before upgrade is necessary. This value can be translated to peak charging power by multiplying the peak load by the maximum allowable EV penetration. For this example, there can be approximately 3.48 MW\textsubscript{pk} of EV charging on top of the current residential load before the feeder will need upgrading.
In a feeder without voltage regulation technology, it can also be important to determine the percentage of penetration of EVs will cause under-voltages. This can be remedied by adding voltage regulating equipment to the feeder, but is desirable to delay as long as possible. Like the current maximum, the voltage minimum will occur at the highest level of loading on the feeder. For residential, this is in the evening. As previously stated, this is also when EV charging occurs. Therefore, EVs will directly impact the voltage minimum on the feeder as well.

Similarly with calculating the current maximum, the percentage of penetration of electric vehicles (daily peak of EV charging divided by the daily peak of the demand of the feeder less the EV charging) is increased incrementally though numerous simulations. The resultant minimum voltage level from each permutation of the simulation can be then plotted against the percentage of penetration of EVs to determine the maximum EVs the feeder can handle, seen in Figure 34.

![Figure 34: Electric Vehicle Charging’s Effects on Base Feeder Voltage](image)

Therefore, for this particular example, the maximum percentage of the demand that can be comprised of EVs is approximately 51% before voltage will dip below 95% of the nominal value. Moving
beyond this percentage of penetration would create under-voltages on the feeder, making voltage regulating equipment necessary.

7.3 Photovoltaic Generation

This section investigates the effects that photovoltaic generation has on the base feeder configuration. This will be used as a secondary base case when adding other technologies such as EVs and a BESS. In the case of generation, current is provided to the system. At some point, the generation will supply more current that the feeder cabling can handle based on its ampacity rating. In this case, the most heavily loaded cable will be closest to the photovoltaic generation.

This will be studied in a similar fashion to determining the maximum EVs a feeder can accommodate in Section 7.2. Unlike determining the maximum allowable EV penetration, photovoltaic generation operates during the day and does not impact the peak loading period of the demand curve being studied. A depiction of adding various size photovoltaic generation to the residential load curve can be seen in Figure 35.
By using a similar approach taken in determining the maximum number of EVs, the amount of PV generation will be incrementally increased while the maximum current value is recorded. This produces a maximum PV output vs. maximum (absolute value) current seen on the feeder, shown in Figure 36.

Figure 35: Maximum PV Generation Before Feeder Overload on Base Feeder Configuration
It can be seen that there can be a substantial amount of generation installed on this particular feeder relative to the amount of load. As long as the maximum PV generation is below approximately 26MW, the feeder cabling will not be overloaded by the back-feeding power generation.
7.4 System with BESS

This study entails the base case feeder (from section 7.1) with a BESS running the dynamic programming optimization discussed in Section 4.1. Because the dynamic programming algorithm is concerned chiefly with the economic benefit of the system and not the electrical optimum the BESS will reduce the demand during the peak cost period, not necessarily the peak demand period. The algorithm is applied to the load curve used in the base case example and Figure 37 depicts the power demanded from the substation while Figure 38 and Figure 39 display the BESS power output and cost of electricity respectfully (based on results shown in section 2.5).

![Load + BESS for Economic Optimization](image)

**Figure 37: Optimum Economic BESS Charge/Discharge Applied to Base Case Feeder**

![BESS Output for Economic Optimization](image)

**Figure 38: Optimum Economic BESS Charge/Discharge**
Using the dynamic programming algorithm, the BESS makes a profit of approximately $72/day by charging during periods of low LMP and discharging during high periods of LMP. Using the simple calculation described in 3.7 and an estimated capital cost of the BESS at $1.5M (a conservative estimate based upon United States Department of Energy and Electric Power Research Institute’s reporting [41]), the payback is 57 years. Since many BESS technologies are in developmental stages, the capital cost is an estimated value. The payback calculation does not include maintenance costs. However, with such a high time for payback to occur, this simulation shows that energy time-shift alone, in this particular example, is not feasible economically unless the BESS lifetime is greater than 57 years.
7.5 Electric Vehicle Penetration and Distributed Generation

In energy conscious areas it is likely that EVs and PV generation will be coupled. Therefore, it is important to understand how the two technologies interact. Figure 40 shows the base case feeder introduced in Section 7.1 with EV load and PV generation added. Generation is shown as a negative load.

It can be seen that the PV generation is during the day, while the EV load is in the evening and into the night. Therefore, the energy that is produced by the PV generation cannot be made use of by the EV loading unless stored by an energy storage device for later use. This is a particularly important point for energy conscious communities that may want to utilize the nature of renewable energy in their car to minimize their commuting carbon footprint.
7.6 BESS and Electric Vehicle Penetration

In the case that have high percentages of EV charging causing cabling to be near or over its ampacity, energy storage can be used to decrease demand during these peak periods by supplying power downstream of the congested area. The peak LMP may not fall exactly during the peak demand, but by ensuring the BESS charges at the lowest LMP still acts as generation during peak LMP values, economic gains from energy time-shifting can be found. In the previous example of optimum BESS economic operation through dynamic programming, it was seen that the BESS was operating as generation during the peak demand of the example load curve. Therefore, this charge/discharge schedule will be used. A depiction of this scenario can be seen in Figure 41.

![Figure 41: Applying EV Charging and Optimum Economic BESS Output to Base Case Feeder Demand](image)

It will be assuming that the BESS lifetime is 20 years and the interest rate is 5%. Therefore, the present value of the $72/day is calculated using the present worth equation shown in 2.3 to be $327,507, seen in .


\[
\text{Present Worth of Energy Time – Shift} = (72 \times 365) \left[ \frac{(1 + .05)^{20} - 1}{0.05(1 + .05)^{20}} \right] = \$327,507 \quad (36)
\]

The other benefit the BESS creates in this scenario is the possible deferment of feeder upgrade by decreasing the peak load to delay feeder overload. If feeder upgrade was deferred, the avoided cost of the upgrade could be invested until the upgrade was necessary. The potential earnings of this investment represents a benefit for deferral. If this earning, in present value, is greater than the capital cost of the BESS, then the purchase of the BESS is justified.

Feeder upgrade is estimated at $350,000/mi. or $2.1M for the entire feeder. As with the previous calculation, the interest rate will be assumed to be 5%. The amount of time the BESS extends the life of the feeder without upgrade is dependent on the percentage increase of peak load and will therefore be varied from case to case. For this example, it will be assumed that the BESS extends the life of the feeder by 10 years. Therefore, the present worth of the feeder upgrade 10 years into the future is $3.42 M. This produces earnings of $1.32M by investing the avoided feeder upgrade cost.

\[
\text{Capital Deferment Benefit} = 2.1M \times (1 + .05)^{10} - 2.1M = \$1,320,680 \quad (37)
\]

These benefits can then be used in the cost benefit ratio discussed in Section 2.3 to determine if the project’s feasibility. Like the calculation in Section 7.4, it will be assumed that the BESS cost is $1.5M.

\[
B - C \text{ Ratio} = \frac{1320680 + 327507}{1500000} = 1.09879 \quad (38)
\]

It can be seen from this equation that this project is in fact economically justifiable, by slim margins. Therefore, it is seen that combining use cases can produce positive economic results when justifying the use of BESSs.
7.7 BESS, Electric Vehicle Penetration, and Photovoltaic Generation

This section investigates how the technologies of BESS, EVs, and PV generation coincide. In this case, the BESS will be charged during times when PV generation is occurring. Therefore, the BESS can be charged without buying additional energy from the grid. This energy can then be used to decrease the amount of energy bought during high LMP periods. As seen in section 7.6, this also aligns with the peak demand for the example residential demand curve and can be used to defer feeder upgrade by alleviating overload scenarios when the demand is in danger of creating a cable overload. A depiction of this scenario can be seen in Figure 42.

![Figure 42: Applying EV Charging, PV Generation, and Optimum Economic BESS Charge/Discharge to the Base Case Demand](image)

Unlike the payback considered in Section 7.6, the energy in the BESS is essentially at no cost due to the nature of its fuel source. Therefore, the entire 2.5MWh energy capacity is profit in terms of cost.
avoidance. This brings the BESSs’ daily profit up to $132.5/day, or $48,362.50/year. In this case, like the previous cases, maintenance costs will be assumed to be small enough to be ignored. Using the same 5% interest and 20 year lifetime assumed in previous sections yields a present worth of $602,704 in terms of energy-shift cost avoidance over the lifetime of the BESSs’ operation, seen in Equation 39.

\[ \text{Present Worth of Energy Time} - \text{Shift} = 48362.5 \left[ \frac{(1 + .05)^{20} - 1}{0.05(1 + .05)^{20}} \right] = 602,704 \]  

(39)

The same capital deferment savings can be used from Section 7.6 and therefore the benefit-cost ratio can be directly calculated, seen in Equation 40.

\[ B - C \text{ Ratio} = \frac{1320680 + 602704}{1500000} = 1.60282 \]  

(40)

It can be seen that the benefit-cost ratio is much higher than 1.0 and therefore this system is strongly economically justifiable. Therefore, it can be seen that by using renewable energy in a system with a BESS that is making use of multiple use cases in the form of energy time-shift and feeder upgrade deferral, the economic justification for the BESS capital cost can be strongly justified. However, this does depend heavily on feeder loading, cost of electricity, BESS size, cost, capacity (power and energy), and efficiency.
7.8 BESS for Stability

This section outlines an example result of the use of a BESS for stability purposes. In the case where there is a concentration of loads that are particularly sensitive to outages, it may be desirable to form them into a microgrid that has the ability to isolate from the macro electric grid. In this case, when the microgrid is operating in isolation it is at greater risk to instability due to faults within the system. This is due to the limited amount of mechanical inertia in the system.

Adding additional generation to the system is one possible solution to this problem; however there are numerous benefits to using a BESS. In the case where the microgrid must become isolated instantaneously due to an external incident, a BESS can instantaneously take on the load of the microgrid while the generation within the system gets up to speed. Rotating machinery can never be as instantaneous as BESS. In some instances a small rotating machine can be quick enough to perform this backup functionality, but for a system wide solution there would need to be numerous units.

Therefore, in this example a BESS has been added to the same bus as the only microgrid rotating swing generation to reduce the chance of a fault isolating the generation and BESS, as seen in Figure 46. In this example, the pre-fault maximum power will be set arbitrarily at 1.6 pu, the fault will reduce the load by approximately 70%, and clearing the fault will result in a maximum power reduction of approximately 45% from the original 1.6pu. These values can be modified or applied to any existing system or fault. The mechanical input to the generator will be at 1pu pre-fault. This means that the mechanical input to the generator will need to decrease in order to have an intersection with the post-fault power-angle curve, and therefore, a stable operation point. Since it is standard practice to have this operation point below the maximum power output, .65pu will be chosen. It can be seen in the summary of this fault example in Figure 43 to be at 0.65pu and well below the post-fault maximum power of 0.9pu.
When the fault occurs on the system, it is impossible for the BESS to aid in the situation due to the short circuit path created by the fault. The duration of the fault is determined by how fast the protection scheme isolates the faulted portion of the line. This is done by opening circuit breakers on all sides able to contribute energy to the fault. For this example a reasonable fault clearing time of 160ms will be assumed.

When a rotating machine is not operating at the intersection of its mechanical input and the current power-angle curve, the angle will increase until the equilibrium between mechanical and electrical power is found. It can be seen that, in this example, the post fault power-angle curve has no intersections with the pre-fault mechanical input. This will result in an unstable condition if the mechanical input is not lowered to the point there is an intersection between the post fault power-angle curve and the post-fault mechanical input. However, this adjustment to mechanical input can take time. If this adjustment takes too long, the system may already have reached an unstable condition. For this example, the pre-fault rotor angle will be assumed to be at 40 degrees.

The BESS will act as a variable load while the generator governor adjusts to the new steady state electrical power demand. The amount of power the BESS will consume will be the difference between
the electrical demand and mechanical input to the generator, which will be decreasing to match the electrical demand over time. By inspection of the swing equation (Equation 35), it can be seen that by equalizing the mechanical and electrical power the rotor angle acceleration will be stopped. Therefore, the rotor angle will accelerate during the fault and will be held constant post-fault until the mechanical power has an intersection with the post-fault power-angle curve. At this point the BESS will cease to perform as a load. The rotor angle will then oscillate until it settles on the operation point. Figure 44 shows the rotor angle oscillating where the oscillations are not growing. In this case, damping was not taken into account and the oscillations shown depict a stable scenario.

![Figure 44: Rotor Angle Held Constant Post-Fault While Generator Governor Adjusts to New Steady State Electrical Power](image)

The stable situation can also be seen in Figure 45. The circular figure shows that the oscillation is not growing, and is therefore a stable condition. It is more oval shaped because it is on the threshold of instability. The tail in the middle of the shape is the fault period, where the angle was originally at rest and quickly accelerated until eventually falling upon the stable power-angle curve. Due to the study being on the margin of stability, this would be the smallest possible BESS that could be used for stability. To decrease the risk of an unstable condition a BESS that is larger than this minimum value by a reasonable safety margin should be used.
The sizing of a BESS for this functionality depends heavily on the power rating of the unit since the duration of the use is small. The BESS must make up for all lost load for a short period of time. Therefore, the larger the amount of load that is isolated by the fault clearing protection, the larger power capacity is needed by the BESS. Since the BESS will be acting a load for the differential between the pre and post fault power, the maximum allowable difference should be the power rating of the BESS.

\[
BESS \text{ Power Capacity} = \text{Max. Load} - (\text{Max. Load During Fault}) \times (1 - \text{Safety Margin})
\] \hspace{1cm} (41)

To determine the exact necessary energy capacity required for stability purposes a stability simulation must be run to determine how long the BESS must operate as a load in order for the generator governor to settle on the post fault power. Once this simulation is run, the power input to
the BESS must be integrated over the duration of its use as a load. However, a worst case energy capacity can be found using static values, seen in

\[ \text{Energy Capacity} = \left( \frac{1}{2} \right) (\text{Governor Max. ROC})(\text{BESS Power Capacity})^2 \]  

(42)

In this equation the maximum amount of power that the mechanical input will need to change is represented by the maximum BESS power capacity, if rated properly through previous calculations. By multiplying this by the governor’s maximum rate of change, in units of power per time, the amount of time needed for the governor to adjust to the worst case post-fault power can be found. By multiplying this value again with the BESS rated power capacity the amount of energy needed to output the maximum power for that amount of time. Because the governor rate of change is assumed to be a fixed value, this will result in a constant decrease in necessary power intake from the maximum power rating to zero. The area calculated by multiplying the maximum power by the time gives the energy for maximum output for this entire duration. With a fixed decrease in output due to the governor, this area can be cut in half.

There must be power monitoring and circuit breakers available at numerous points throughout the system in order to effectively implement this system. If a load is downstream of an isolation point, but upstream of a fault, it is load that must be disconnected in order to isolate the fault. However, if there had been another possible isolation point between the fault, this load may not have been disconnected. Therefore, it can be realized that the more isolation points available, the less load that may have to be shed unnecessarily. However, in a radial feeder (seen in Figure 46), all down-stream loads from the fault will be disconnected.

![Figure 46: Radial Feeder](image)

Figure 46: Radial Feeder
Therefore, if a microgrid were to be configured in a circular fashion (seen in Figure 47), there would be two directions of possible power flow and therefore a single fault could be isolated independently from the rest of the system. To increase redundancy, tie lines across the circular feed can be added.

Combining a properly sized BESS with appropriate feeder configuration and smart grid technology, it has been shown that the stability of a microgrid can be greatly increased with the addition of a BESS.

### 7.8.1 Simple Stability Example

This section will briefly explain classic stability analysis. This analysis is the basis of Section 7.8 that is extended to be used with a BESS for stability. A system will be introduced with an example fault location [42]. It is desired to determine the critical clearing time of the fault to maintain stability. In other words, it is desired to find the maximum amount of time the fault can be active on the line before the generation cannot recover from the rotor angle swing. The basic system to be studied can be seen in Figure 48.
The following values are to be used:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Voltage</td>
<td>1.2 pu</td>
</tr>
<tr>
<td>( Z_G )</td>
<td>j0.0</td>
</tr>
<tr>
<td>( Z_1 )</td>
<td>j0.25</td>
</tr>
<tr>
<td>( Z_{L1} )</td>
<td>j0.58</td>
</tr>
<tr>
<td>( Z_{L2} )</td>
<td>j0.43</td>
</tr>
<tr>
<td>( Z_{L3} )</td>
<td>j0.43</td>
</tr>
<tr>
<td>( Z_2 )</td>
<td>j0.17</td>
</tr>
<tr>
<td>Grid Voltage</td>
<td>1 pu</td>
</tr>
<tr>
<td>Grid Angle</td>
<td>0° (Reference)</td>
</tr>
<tr>
<td>Inertial Constant (H)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The first step will be to determine the pre, during, and post power angle curves. Power-angle curves depict the available electrical power output of the generator vs. it’s rotor angle for a given transfer reactance. Therefore, transfer reactance’s from generation to grid (infinite bus) must be found for all scenarios. These can be found using standard circuit analysis methods. The pre-fault reactance is thus found below.

\[
X_{\text{trans before}} = 0.25 + 0.17 + \frac{0.58}{2} = 0.71 \text{ pu}
\]

With the values known, this can be directly translated into the pre-fault power-angle curve.

\[
P_e^{\text{Before}} = \frac{EV}{X_{\text{before}}^{\text{trans}}} \sin \delta = \frac{1.2 \times 1.0}{0.71} \sin \delta = 1.69 \sin \delta
\]

It is also necessary to determine the starting point of the rotor angle. This is done by using the relation of the operating point (electrical power operating point) with the maximum point of the power-angle curve.
\[
\sin \delta_0 = \frac{P_e}{P_{max}} = \frac{1.0}{1.69} = 0.592
\]

And therefore,

\[
\delta_0 = \sin^{-1} \left( \frac{1.0}{1.69} \right) = 36.28^\circ
\]

It is easiest to find the during fault transfer reactance by converting the delta created by the fault to ground to a wye and applying typical circuit theory. The result is as follows

\[
X_{trans}^{During} = 0.395 + 0.315 + \frac{0.395 \times 0.315}{0.0725} = 2.426 \text{ pu}
\]

This is turned into a power angle curve in the same manner the pre-fault was and therefore:

\[
P_e^{During} = 0.495 \sin \delta
\]

The post-fault transfer reactance is simply the sum of the impedances \(Z_L, Z_{L1}, \) and \(Z_2,\) which results in 1.0 per unit. This can then be put into a power-angle curve.

\[
P_e^{After} = 1.2 \sin \delta
\]

Plotting the three power-angle curves will give an overview of the power that the generator can produce during each phase of the fault vs. the rotor angle. It can be seen that when the reactance is low, or the system is faulted, the generator cannot produce much power.
The swing equation can now be used to determine the amount of movement the rotor angle will make in each state. The typical round-rotor swing equation is seen below.

\[
\frac{H}{60\pi} \frac{d^2 \delta}{dt^2} = P_m - P_e
\]

The mechanical power will be assumed to be constant at the initial quantity. This is assumed because the fault occurs fast enough that the generator governor cannot adjust. The electrical power will be the corresponding power-angle curve for the scenario. The rotor angle will start at the calculated initial condition. When the fault occurs the electrical power in the swing equation will equal the power-angle curve that is representative for the faulted line. When the fault clears, the electrical power will be the power-angle curve that corresponds to the post-fault system. If the fault is not cleared fast enough, the generator rotor angle will increase to a point of instability.

These equations can be solved and plotted using mathematical software such as MATLAB. This will be the program of choice for this example. For example’s sake the clearing times of 0.09s, 0.1161s, and 0.1162s will be shown. The results for a clearing time of 0.09 can be seen below.
It should be noted that the response is a clean oscillation. This is a characteristic of stability.
It can be seen above that the angle and speed deviation are making an oval. This shows that the oscillations are controlled and stable. The results for a .1161 second clearing time are seen below.
It should be noted that these are still repeating oscillations, so stability is maintained. However, they are becoming less sinusoidal. This is a characteristic of nearing the edge of stability.

The edge of stability can be very noticeable in the plot above. The oval shape is now well pronounced. The rotor angle is moving quickly at some points. Results for a clearing time of .1162s are seen below.
Now it can be seen that the rotor angle has run away. It has moved beyond any valid operation points on the power angle curve and the generator can no longer operate.
This plot no longer resembles any form of circle or oval showing that the oscillations are in fact growing. Since the closest value of stability found was .1161 seconds, it is assumed to be approximately the “critical clearing time”, or the maximum amount of time that a fault can be withstood on the system.
8 Conclusions

This document has introduced the effects new technologies have on the distribution grid. Electric vehicles and renewable distributed generation can have positive environmental impact. However, these technologies complicate the classical operation of the power grid. The once unidirectional power flow becomes bi-directional and, in some instances, can be sectionalized into microgrids that have the ability to operate in complete isolation. These complications can produce negative side effects including overloads on cables, voltage situations, and stability concerns, but can also create positive benefits such as a more stable macro-grid comprised of many microgrids and the reduction of dependence on fossil fuels both in power generation and automotive transportation. A possible solution to ease the transition to a more modern electrical power grid is to make use of large capacity energy storage systems.

In this document, BESSs were considered in particular due to their quick power response inverter technology output and scalable size. Electric vehicle technology and its proliferation were investigated to determine appropriate power consumptions that should be used for simulations. Typical load profiles with statistical analysis were portrayed along with typical marginal pricing. All of these values were made use of in the modeling environment that calculated electrical and economic values. Various test feeders were shown in this modeling environment to make use of the three main BESS charge/discharge algorithms:

1. dynamic programming for economic optimization
2. maximum smoothing of renewable generation (rate of change limiting)
3. maximum peak shaving

Economic analysis found that the BESS can be economically justified if paired with appropriate technologies in a multi-use-case scenario. However, it is important to note that the BESS was also shown to be a valuable resource for stability purposes that are significantly harder to economically justify. However, due to the stability function’s need for high power output and low energy, these use cases can be integrated concurrently with minimal sacrifice to other economic uses. Therefore, the BESS can supply the microgrid load while the local generation is ramping up to meet demand directly after isolation, can be used as an energy-time shift for any renewable generation within the microgrid, and greatly enhance stability if a fault were to occur within the system while isolated from the macro electric power grid.
The most economically beneficial scenario displayed in this document was found when a BESS, PV generation, and EV charging were combined on a residential load profile where the BESS shifted the renewable energy to the peak demand period of the day and also deferred the capital investment of feeder upgrade due to overloading. It was also found that large percentages of EV charging and PV generation can be added to a typical residential feeder without necessarily calling for immediate feeder upgrade. However, when EV charging does push the limits of the ampacity of the feeder, economic justification can be found in installing a BESS for capital deferment paired with optimum economic charge/discharge based on the local price of electricity throughout the day. In conclusion, battery energy storage systems have the potential for economic viability when employed in multi-use case scenarios.
References


