ABSTRACT

HAMBRIDGE, SARAH MABEL. Frequency Based Real-time Pricing for Residential Prosumers. (Under the direction of Dr. Alex Q. Huang and Dr. Ning Lu.)

This work is the first to explore frequency based pricing for secondary frequency control as a price-reactive control mechanism for residential prosumers. A frequency based real-time electricity rate is designed as an autonomous market control mechanism for residential prosumers to provide frequency support as an ancillary service. In addition, prosumers are empowered to participate in dynamic energy transactions, therefore integrating Distributed Energy Resources (DERs), and increasing distributed energy storage onto the distributed grid.

As the grid transitions towards DERs, a new market based control system will take the place of the legacy distributed system and possibly the legacy bulk power system. DERs provide many benefits such as energy independence, clean generation, efficiency, and reliability to prosumers during blackouts. However, the variable nature of renewable energy and current lack of installed energy storage on the grid will create imbalances in supply and demand as uptake increases, affecting the grid frequency and system operation. Through a frequency-based electricity rate, prosumers will be encouraged to purchase energy storage systems (ESS) to offset their neighbor's distributed generation (DG) such as solar.

Chapter 1 explains the deregulation of the power system and move towards Distributed System Operators (DSOs), as prosumers become owners of microgrids and energy cells connected to the distributed system. Dynamic pricing has been proposed as a benefit to prosumers, giving them the ability to make decisions in the energy market, while also providing a way to influence and control their behavior. Frequency based real-time pricing is a type of dynamic pricing which falls between price-reactive control and transactive control. Prosumer-to-prosumer transactions may take the place of prosumer-to-utility transactions, building The Energy Internet. Frequency based pricing could be a mechanism for determining prosumer prices and supporting stability in a free, competitive, market.

Frequency based pricing is applied to secondary frequency control in this work, providing support at one to five minute time intervals. In Chapter 2, a frequency based pricing curve is designed as a preliminary study and the response of the prosumer is optimized for economic dispatch. In Chapter 3, a day-ahead schedule and real-time adjustment energy management framework is presented for the prosumer, creating a market structure similar to the existing energy market supervised by Independent System Operators (ISOs). Enabling technology, such as the solid state transformer (SST) is described for prosumer energy transactions, controlling power flow from the prosumer's energy cell to the grid or neighboring prosumer as an energy router. Experimental results are shown to demonstrate this capability. Additionally, the SST is capable of measuring the grid
Lastly, a frequency based real-time hybrid electricity rate is presented in Chapter 4 and Chapter 5. Chapter 4 specializes in a single direction rate while Chapter 5 presents a bi-directional rate. A Time-of-use (TOU) rate is combined with the real-time frequency based price to lower energy bills for a residential prosumer with ESS, in agreement with the proposed day-ahead and real-time energy management framework. The cost to the ESS is also considered in this section. Linear programming and strategic rule based methods are utilized to find the lowest energy bill. As a result, prosumers can use ESS to balance the grid, reducing their bill as much per kWh as PV or DG under a TOU net-metering price scheme, while providing distributed frequency support to the grid authority. The variability of the frequency based rate is similar to variability in the stock market, which gives a sense of how prosumers will interact with variable prices in a system supported by The Energy Internet.
Frequency Based Real-time Pricing for Residential Prosumers

by
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DEDICATION

To my parents and my sisters.
BIOGRAPHY

Sarah grew up in Charlotte, North Carolina where her parents taught her to value creativity and experimentation at a young age. Her mom was always using the kitchen table for one project or another, passed on from her grandfather who had quite the workshop in his basement. She grew up interested in science, and studied Applied Science - Biomedical Engineering at the University of North Carolina at Chapel Hill, from which she graduated in 2011. Her passion for environmental issues, including the increased discussion of climate change and marine impact of oil spills inspired her to study electrical engineering and research alternate energy resources and systems at the neighboring rival university, North Carolina State. She plans to think about electricity forever, as the modern electric smart grid is born and evolves with the explosion of clean tech and the sharing economy. Her next step will be joining a small company, to pioneer blockchain in the energy space.
ACKNOWLEDGEMENTS

I have grown and changed immensely in the six years I have called Raleigh home and have worked as a student and researcher at North Carolina State University. I would first like to thank my parents and my sisters for their unwavering love and support of my studies and future career. Thank you to my parents especially, who have always believed in me at times when I did not believe in myself, who have offered professional guidance and emotional support, and who have always been just a phone call or short 3 hour drive away. I am also incredibly grateful to my sisters. Together we have experienced life by each other's side, supporting each other's passions, goals, and adventures as similar or different as they may be.

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TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... viii

LIST OF FIGURES .......................................................................................................... ix

Chapter 1  INTRODUCTION .......................................................................................... 1
  1.1 Grid Ancillary Services and DERs ................................................................. 1
    1.1.1 Existing Ancillary Services and Reliability ........................................... 2
    1.1.2 Moving Towards DERs and Distributed Solar ..................................... 3
  1.2 Frequency Control ......................................................................................... 6
    1.2.1 The Concept of Grid Frequency ............................................................. 6
    1.2.2 Frequency Response and Regulation ..................................................... 7
  1.3 Evolution of the U.S. Electric Grid ................................................................. 9
    1.3.1 A Move Towards Deregulation ............................................................... 9
    1.3.2 DSOs and The Retail Market ................................................................. 11
    1.3.3 Dynamic Pricing and Transactive Energy ............................................. 18
  1.4 Microgrid Control ......................................................................................... 21
  1.5 The Concept of the Energy Internet .............................................................. 23
    1.5.1 Required Technologies ........................................................................ 23
    1.5.2 Zero Marginal Cost Society ................................................................. 25
  1.6 Proposed Pricing Scheme and Contribution ................................................. 26
  1.7 Outline ............................................................................................................. 27

Chapter 2  A DYNAMIC FREQUENCY BASED PRICE .................................................. 28
  2.1 Motivation ..................................................................................................... 28
  2.2 Background .................................................................................................. 29
    2.2.1 Prior Art ............................................................................................... 29
    2.2.2 What is a Prosumer? ........................................................................... 31
  2.3 Frequency Data ............................................................................................ 31
  2.4 Pricing Scheme ............................................................................................ 32
  2.5 Prosumer Response ...................................................................................... 35
    2.5.1 Simulation Results ................................................................................ 36
  2.6 Conclusion .................................................................................................... 38

Chapter 3  MARKET STRUCTURE AND ENABLING TECHNOLOGY ....................... 39
  3.1 Market Structure for Residential Prosumers ................................................. 39
    3.1.1 Proposed Day-Ahead Schedule and Real-time Adjustment ................. 40
  3.2 Solid State Transformer (SST) ................................................................. 41
    3.2.1 SST as an Energy Router ..................................................................... 42
    3.2.2 Power Flow Regulation ................................................................. 43
    3.2.3 Experimental Results ........................................................................ 46
  3.3 Conclusion .................................................................................................... 47
Chapter 4  SINGLE DIRECTION TOU AND FREQUENCY BASED HYBRID ELECTRICITY RATE  
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Indroduction</td>
<td>49</td>
</tr>
<tr>
<td>4.2 TOU+Freq Hybrid Rate</td>
<td>49</td>
</tr>
<tr>
<td>4.3 Linear Programming Model</td>
<td>50</td>
</tr>
<tr>
<td>4.4 Single Direction Power Flow Results</td>
<td>50</td>
</tr>
<tr>
<td>4.4.1 Two Different Days of Frequency Data</td>
<td>55</td>
</tr>
<tr>
<td>4.5 Conclusion</td>
<td>61</td>
</tr>
</tbody>
</table>

Chapter 5  BI-DIRECTIONAL TOU AND FREQUENCY BASED HYBRID ELECTRICITY RATE  
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Problem Set-Up and Methods</td>
<td>62</td>
</tr>
<tr>
<td>5.2 Frequency Based Rate Design</td>
<td>65</td>
</tr>
<tr>
<td>5.2.1 Design Parameters</td>
<td>67</td>
</tr>
<tr>
<td>5.2.2 Variation in Daily Frequency</td>
<td>70</td>
</tr>
<tr>
<td>5.3 Cost to Energy Storage System (ESS)</td>
<td>71</td>
</tr>
<tr>
<td>5.4 Rule Based Prosumer Response Method</td>
<td>76</td>
</tr>
<tr>
<td>5.5 Daily Average Energy Bill for Home A, B, C, and D</td>
<td>83</td>
</tr>
<tr>
<td>5.6 Thirty-two Home Study</td>
<td>83</td>
</tr>
<tr>
<td>5.7 Conclusion</td>
<td>91</td>
</tr>
</tbody>
</table>

Chapter 6  CONCLUSION AND FUTURE WORK  
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Conclusion</td>
<td>93</td>
</tr>
<tr>
<td>6.2 Future Work</td>
<td>94</td>
</tr>
</tbody>
</table>

BIBLIOGRAPHY  
<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
</tr>
</tbody>
</table>
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A Summary of U.S. Electricity Deregulation [Su14]</td>
<td>12</td>
</tr>
<tr>
<td>1.2</td>
<td>North Carolina - Schedule R-TOU, Prices</td>
<td>18</td>
</tr>
<tr>
<td>2.1</td>
<td>Results, Energy Cost in $</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Rates, price/kWh</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Upper and Lower Bounds for Optimization Variables, in kW except for SOC (out of 1)</td>
<td>55</td>
</tr>
<tr>
<td>4.3</td>
<td>Energy Cost for One Day ($), Source: Pecan Street Inc. Dataport 2016</td>
<td>57</td>
</tr>
<tr>
<td>4.4</td>
<td>Daily Energy Bill ($) for House A, B, and C for Frequency Day 1 and Day 2</td>
<td>59</td>
</tr>
<tr>
<td>4.5</td>
<td>Daily Energy Bill for Home A, B, C, and D using Linear Programming to Optimize for the TOU rate and TOU+FREQ Rate ($)</td>
<td>67</td>
</tr>
<tr>
<td>4.6</td>
<td>Daily Energy Bill ($) for Home A and B for five different days of frequency data</td>
<td>71</td>
</tr>
<tr>
<td>4.7</td>
<td>Daily Average SOC (out of 1) and ESS Cost ($) for Home A and B for five different days of frequency data</td>
<td>75</td>
</tr>
<tr>
<td>4.8</td>
<td>Rule Based Prosumer Response Method, according to $t = \text{time in minutes}$</td>
<td>82</td>
</tr>
<tr>
<td>5.1</td>
<td>Daily Energy Bill and ESS Cost ($) for Home A and B for five different days of frequency data using linear programming and two prosumer response methods</td>
<td>82</td>
</tr>
<tr>
<td>5.2</td>
<td>Daily Average Energy Bill ($) for Home A, B, C, and D, Comparing TOU Rate to TOU+FREQ Rate for five different days of frequency data</td>
<td>83</td>
</tr>
<tr>
<td>5.3</td>
<td>Eight Homes Defined for Each Group in the Thirty-Two Home Study</td>
<td>85</td>
</tr>
<tr>
<td>5.4</td>
<td>Daily Energy Bill and ESS Cost ($) for Group A and B using linear programming and two prosumer response methods for Frequency Day 1</td>
<td>91</td>
</tr>
<tr>
<td>5.5</td>
<td>Daily Energy Bill ($) for 32 Home Study Comparing TOU Rate to TOU+FREQ Rate using the Response Curve method for Frequency Day 1</td>
<td>91</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1.1 Types of ERS, Functions, and Consequences Without Available ERS [Nera] . . 2
Figure 1.2 US Solar PV Installations 2000-2015 [Mun16] ................................. 4
Figure 1.3 Median Installed Price of Solar in the US from 1998-2015 [Bar16] .......... 5
Figure 1.4 CAISO Duck Chart, Net Load, March 31 [Cai] ............................... 6
Figure 1.5 Typical Residential Solar Profiles, from installations in Austin, Texas, May 2012, Source: Pecan Street Inc. Dataport 2016 .......................... 7
Figure 1.6 The Analogy of Using Water Level in a Container to Explain Power System Frequency [Eto10] .................................................... 8
Figure 1.7 Grid Frequency and Levels of Response, adapted from [Kir02] ............... 9
Figure 1.8 U.S. and Canadian ISOs and RTOs [Iso] ........................................ 10
Figure 1.9 Towards a Deregulated Power System [Ipa11] ................................ 13
Figure 1.10 The DSO as a link between the bulk system operator (Balancing Authority, ISO/RTO) and the microgrid demand-side owners and operators (Prosumers) [RM14] ................................................................. 14
Figure 1.11 Southern Edison TOU rate .......................................................... 17
Figure 1.12 Duke Energy Progress TOU rate .................................................. 18
Figure 1.13 Energy Management Approaches for Distributed Grids [KW16] ........ 19
Figure 1.14 Where Reliability and Economics Intersect [Ipa11] .......................... 22
Figure 1.15 Components of The Energy Internet [Ver12] ................................ 24
Figure 1.16 A Resilient Node for The Energy Internet ..................................... 25

Figure 2.1 Prosumer as an Energy Cell ......................................................... 32
Figure 2.2 Solar (PV), Load, and Frequency curves for one day, 5 min data .......... 33
Figure 2.3 Frequency Spectrum UK, 5 min data .......................................... 33
Figure 2.4 Frequency vs. Price ................................................................. 34
Figure 2.5 Prosumer Response, DESD Power vs. Price ................................. 35
Figure 2.6 SOC Results for Table 2.1, rows 1, 3, 7 ....................................... 38

Figure 3.1 Prosumer Energy Management Framework ..................................... 40
Figure 3.2 Energy Management Framework: Day-Ahead and Real-Time Price Examples and Resulting SOC Curves For Prosumers .......................... 41
Figure 3.3 SST Capabilities ........................................................................ 42
Figure 3.4 SST as an Energy Router Concept .............................................. 43
Figure 3.5 SST Energy Router and the DC Microgrid Energy Cell Configuration, where the prosumer is the owner and operator of the Energy Cell 44
Figure 3.6 Control Diagram for SST Power and Voltage Control Loop .......... 44
Figure 3.7 Battery Droop Control .............................................................. 45
Figure 3.8 Open Loop Test Results ............................................................ 45
Figure 3.9 Demonstration Plan ................................................................... 46
Figure 3.10 Experimental Results ............................................................... 47

Figure 4.1 Frequency moving average ......................................................... 50
Figure 4.2 Price vs. Moving Average ........................................................... 51
Chapter one will provide some background as to why frequency based support should be proposed as an ancillary service provided by residential prosumers. Existing ancillary services will be discussed within the framework of grid reliability and frequency control. Future residential customers will become prosumers as they begin to produce their own energy generation thanks to increased participation of Distributed Energy Resources (DERs) in the energy mix. Control strategies for microgrid management and DERs will be reviewed. Lastly, evolution of the current system operators and energy markets will be discussed as well as a vision for The Energy Internet of the future. The role of transactive energy, dynamic pricing, and frequency based pricing in these two systems will be discussed, providing a platform on which to build this thesis.

1.1 Grid Ancillary Services and DERs

The price of electricity is influenced by many factors. Residential, commercial, and industrial class customers typically follow a rate determined by the utility and approved by the local regulatory commission. Customer rates can be flat or variable. The fixed costs of grid infrastructure and construction of generation plants must be fairly allocated as well as operating costs, related to fuel, maintenance and operation, and based on market prices and customer behavior (demand). The
utility must also provide reliable service achieved through grid balancing. Ancillary services are additional electricity costs that reflect specialty services and functions provided by the grid to ensure coordination of supply and demand.

1.1.1 Existing Ancillary Services and Reliability

The Federal Energy Regulatory Commission (FERC) defines ancillary services as

"Those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services." [Nera]

![Figure 1.1 Types of ERS, Functions, and Consequences Without Available ERS [Nera]](image-url)
The means to provide these services are often broken down into frequency control, spinning reserves, and operating reserves. Frequency control ensures that the grid frequency remains stable around its nominal value, 60 Hz, in the US. Spinning and operating reserves are generators used to meet increases in demand. Spinning reserves are generators already online that can quickly increase their power output. Operating reserves cannot respond as quickly, but can be dispatched by the operator to support the load.

The North American Electric Reliability Corporation (NERC), a nonprofit dedicated to the reliability of the bulk power system, separates essential reliability services (ERSs) into two categories: voltage support and frequency support. ERSs are said to include all ancillary services, which mostly fall in the frequency support category. Fig. 1.1 explains the two categories of ERSs, mentioning the common ancillary services in the Frequency Support column. Spinning and operating reserves fall into the load balancing category described there.

As the grid evolves in today's market, increased generation from Distributed Energy Sources (DERs), like solar photovoltaics (PV), wind, and energy storage, may change the requirements needed for maintaining ERSs to achieve a reliable and resilient grid. Components like demand response are becoming a bigger part of the resource mix in some areas. System operators in various regions such as California, Hawaii, Texas, and Germany have adjusted their operating procedures to account for these changes in the resource mix and trends toward distributed generation.

However, except for cases of demand response, ERSs are not typically fulfilled by customers or prosumers, especially in the residential class. Further, an entity supplying ancillary services is usually contracted, notified to provide service, and then compensated later. In a centralized operating system, one entity has control over all of the resources. As will be explained later, there are many benefits to transitioning to a deregulated operating system and energy market, which will provide more opportunities for DERs and DG to support and enhance the bulk power system. First, the rise of DERs will be discussed.

1.1.2 Moving Towards DERs and Distributed Solar

Concerns about environmental pollution, global warming, and energy insecurity have supported exploration of alternative and renewable forms of electricity. Unlike coal plants and gas turbines, renewable sources like solar and wind as well as storage technologies like battery devices and electric vehicles can be more easily integrated into cities and homes. Instead of a centralized plant located miles away, solar PV and electric vehicles, for example, can be found at the residential level. Producing power on the distributed level has many advantages, including energy efficiency, avoided costs, power outage mitigation, critical power support during outages, financial incentives due to
policy, and ability to be compensated by grid providers for generation and grid services [Ny].

Distributed Energy Resources (DERs) are considered "behind the meter" power generation and storage resources such as solar PV, combined heat and power (CHP) or cogeneration systems, microgrids, wind turbines, micro turbines, back-up generators and energy storage. In terms of renewable sources, this work chooses to focus on solar generation at the distributed or residential level where it is expected to grow in the future. Sources like wind generation will also play a role in the energy mix but are less likely to be situated in a prosumer’s own backyard.

![US Solar PV Installations 2000-2015](Mun16)

**Figure 1.2 US Solar PV Installations 2000-2015 [Mun16]**

Fig. 1.2 depicts the growing number of solar installations each year in the US. Both residential and utility installations are growing each year. In addition, the price of installed solar in the US has decreased drastically from 1998 to 2015. In less than two decades, the $/W DC have decreased from $12 to $4 for residential installations, shown in Fig. 1.3. Today’s cost is around $3 per W.

Without energy storage, solar penetration onto the grid creates some challenges. The California Independent System Operator (CAISO) has published their "duck chart" as depicted in Fig. 1.4, acknowledging three operating challenges: short, steep ramps, oversupply risk, and decreased frequency response [Cai]. The "duck chart" is a graph of various net load scenarios, where the net load is the difference between "the forecasted load and expected electricity production from
various generation resources" [Cai]. High solar generation during the day creates a belly to the curve which then steadily increases as solar generation decreases and load increases to its peak in the late afternoon and early evening. The utility must be able to meet these steep ramping requirements. Additionally, the price of electricity will drastically decrease during times of high solar generation, threatening balance of supply and demand. With more solar on the grid, the utility requires more flexible generators available to respond to frequency deviations.

At the residential level, the variability of solar makes management of homes, microgrids, and distribution circuits difficult. As shown in Fig. 1.5, there can be substantial variation on a minute to minute basis. Energy storage poses a solution, but is still a costly technology to residential prosumers who do not have many incentives to invest. A pricing scheme should be allocated to mitigate these challenges so that power and energy balance can be achieved, while transitioning towards high penetration of solar generation on the grid. As mentioned above, frequency support is marketed as an ancillary service and should be extended to residential prosumers and distributed generators as well as energy storage owners in order to incentivize grid balancing on the distributed side. A technical understanding of the grid frequency is described in the next section.
1.2 Frequency Control

1.2.1 The Concept of Grid Frequency

The AC power grid is maintained at a specific frequency, 60 Hz or 60 cycles per second, in the United States, with an operating range of 59.98 to 60.02 Hz. Residential and commercial loads, as well as power system equipment, like transformers, are designed to operate within a narrow band above and below the nominal frequency. The grid frequency itself, is directly correlated to the balance of supply and demand of grid power, known as the balance of generation and load. A good way to visualize the balance of the grid frequency is to think of water in a container, with water pouring in at the top and leaving the container through a hole in the bottom. Fig. 1.6 demonstrates this analogy. If the water flowing in (power generation entering the grid), is flowing at the same rate as the water flowing out (load power being consumed), then the water level of the container (the grid frequency) will remain constant. Overfrequency will occur if there is more inflow of water. Underfrequency will occur if more water is flowing out. The utility can increase or decrease generation, but load can only be increased, typically. Curtailment of demand only happens during emergency situations and demand response is an emerging control mechanism that has not reached widespread use.
The electric grid presents a unique challenge to operators as loads can change instantaneously, affecting the grid balance. Control of frequency must be rapid, automated, and autonomous in order to insure grid reliability and resiliency. Frequency deviations can be responded to by a generator's governor, which controls the speed of the machine, or by utilizing contracted partners who provide frequency regulation as an ancillary service. Generation is allocated to each generator by supplementary control from a control center [Woo13].

As seen in Fig. 1.7, governors and devices providing ancillary services must respond if the frequency leaves the nominal range. Around the limit of 59.1 Hz, under-frequency load shedding will start to occur, which means that loads will involuntarily be dropped from the grid. At the upper and lower limits of 61.5 and 58.5 Hz, the generators will trip in order to prevent equipment damage (see Fig. 1.7).

Frequency control is typically made up of primary control (also called frequency response) and secondary control (also called frequency regulation). Primary control responds within seconds, while secondary control responds within minutes. Other control mechanisms can take place in
the minutes to hours timeframe or longer when considering the long term average frequency. Primary control is used to stabilize the frequency by providing governor action and load. Governors sense a change in speed and adjust energy input to the generator [Nerb]. During underfrequency, generators draw less energy, reducing the load power consumed. Additionally, underfrequency relays interrupt pre-defined or interruptible loads, which may be contracted as ancillary service providers. Secondary control occurs within minutes, and works to restore the grid frequency to its nominal value. It is provided by spinning and non-spinning reserves and achieved by Automatic Generation Control (AGC) [Nerb]. AGC maintains the correct exchange of power between control areas and maintains each generation unit at its most economic value [Woo13]. Supervisory Control and Data Acquisition (SCADA) systems are used to take measurements to determine the net actual interchange between areas and determine the system's net energy balance with its interconnection in real-time [Nerb]. This is done by calculating a balancing area's Area Control Error (ACE) from interchange and frequency data [Nerb]. Each area has a net frequency bias, allowing power transactions between areas. The ACE determines the error between the scheduled bias and the measured frequency and power flow. AGC calculates adjustments and notifies generators in order to reduce the ACE.

Power injection onto the grid can be viewed by the utility as an ancillary service, when conducted during periods of low frequency. As shown in [KL15] the utility will pay a price, an average of 33 Euros/MWh, in this case, for upward frequency regulation. In terms of ancillary services there are often different prices for upward and downward regulation [PA14]. Rules have been developed to compensate frequency regulation according to performance and reliability enhancement which will encourage better use of devices providing ancillary services [PA14][Jin13]. However, these rules should influence the cost of energy in order to affect the behavior of consumers and prosumers at the distribution level. As explained in [Cha11], a frequency dependent price component called the
Unscheduled Interchange Charge was introduced in India in 2002 as part of a pricing scheme called the Availability Based Tariff, creating a real-time market, which has been successful in regulating the Indian grid frequency. Additional control schemes for demand and energy storage have been proposed for this market. The next sections will discuss the potential operating and market structures for a frequency based energy price.

1.3 Evolution of the U.S. Electric Grid

1.3.1 A Move Towards Deregulation

The electric grid is an example of a natural monopoly. It is not cost effective for competing utilities to build their own lines side by side to neighborhoods and consumers. One grid is often the best solution. Naturally, companies began to build and manage the grid as sole providers. In 1880, Thomas Edison established the first investor-owned electric utility in New York City. In the early 1990s, regulation of utilities began to occur. With no competition, customer willingness to buy electricity could not influence the price [Su14]. Regulation by federal, state, and local governments was necessary so that customers would be charged a fair price and utilities could make a fair profit,
while providing reliable, secure, safe service. In this one-directional system, all generation was centralized and managed by the utility in a vertically integrated system. This means that power flows in one direction from large power plants through the transmission infrastructure to the customers. A utility owning the generation, transmission, and distribution is said to be vertically integrated.

Holding companies began to control up to two thirds of the country’s energy trading [Su14], so the U.S. Congress passed the Public Utility Holding Company Act of 1935 (PUHCA) in the spirit of deregulation to break up the holding companies and support smaller monopolies. During the energy crisis in the 1970s, another deregulatory act was passed, the Public Utility Regulatory Policies Act (PURPA) in order to promote utilization of domestic energy sources and renewable energy. Also, non-utility power producers could sell to wholesale markets, increasing competition and providing other options to a vertically integrated system [Su14].

![Figure 1.8 U.S. and Canadian ISOs and RTOs](Iso)

More pressure grew from commercial and industrial customers to negotiate with wholesale power suppliers in the 1980s. The U.S. Congress passed The Energy Policy Act of 1992 (EPACT) to expand deregulation, increase energy use, and energy efficiency. Consumers could not negotiate or choose who to buy from, but transmission owners were required to transmit power for different wholesale providers [Su14]. In 1996, the Independent System Operator (ISO) was born as a product
of FERC Orders 888 and 889. These orders stipulated how transmission owners could charge for access to their lines and be required to give free access in some cases [Su14]. Transmission and generation businesses were determined to be separate and to provide non-discriminatory service. More transparency was supported through information systems. ISOs allowed for a more competitive electricity market, but only at the wholesale level. Competition at the distribution level (the retail electricity market) would provide consumer choice and negotiation power, which has yet to be reached. The current ISOs and Regional Transmission Organizations (RTOs), which operate utility owned transmission lines in the U.S. are shown in Fig. 1.8. The unmarked areas are monopolized by more vertically integrated utilities and are regulated, non-competitive markets.

To finish the history of U.S. electricity deregulation, the Energy Policy Act of 2005 was passed, once again allowing financial holding companies and mergers. Lastly, FERC Order 890 and 719, issued in 2007 and 2008, respectively, strengthened transmission open access, non-discrimination, and improved the competitiveness of wholesale markets [Su14]. A summary of these orders and acts are presented in Table 1.1.

The deregulated power system is illustrated in Fig. 1.9. On the left, the distribution circuit is shown, with the Residential, Commercial, and Industrial customer classes labeled. On the right, the wholesale market is shown, operated by the ISO. Wholesale prices influence the bulk power operation. Pricing is determined day-ahead and real-time and is priced in quantities of energy, ancillary services, and capacity. The distribution system directs power to the customers through the retail market. As will be discussed later, the customer may respond to direct load control and participate in demand response. Distributed generation and electric vehicles may also be connected to the distributed grid. In some areas, the distribution provider may be completely independent to the transmission utility or generators, buying power from the wholesale market and selling to local customers through its own retail.

1.3.2 DSOs and The Retail Market

In order to incorporate more renewable and distributed energy sources (DERs) into the power market, a distributed or decentralized power management system is needed [MS13]. As consumers become prosumers (producers and consumers), a bi-directional, competitive retail market is needed. While the bulk power system has evolved over the years and ISOs, competition, non-discrimination, and distribution-only utilities have emerged, and the same is expected to happen within the distributed power system and within the retail market. The concept of Distributed System Operators (DSOs) has emerged, which would tie into the bulk power system or even replace much of the energy traffic through ISOs.
### Table 1.1 A Summary of U.S. Electricity Deregulation [Su14]

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1935</td>
<td>Congress passes the Public Utility Holding Company Act of 1935 (PUHCA) to require the breakup and the stringent federal oversight of large utility holding companies. The system of federal and state regulations that resulted from this act still exists today.</td>
</tr>
<tr>
<td>1978</td>
<td>Congress passed the Public Utility Regulatory Policies Act (PURPA) which initiated the first step toward deregulation and competition by opening wholesale power markets to non-utility electricity producers.</td>
</tr>
<tr>
<td>1992</td>
<td>Congress passed the Energy Policy Act of 1992 (EPACT), which promoted greater competition in the bulk power market. The Act chipped away at utilities' monopolies by expanding FERC authority to allow independent power producers equal access to the utilities' transmission grid.</td>
</tr>
<tr>
<td>1996</td>
<td>FERC implemented the intent of the Act in 1996 with Orders 888 and 889, with the stated objective to “remove impediments to competition in wholesale trade and to bring more efficient, lower cost power to the nation's electricity customers.”</td>
</tr>
<tr>
<td>2005</td>
<td>Congress passed the Energy Policy Act of 2005, a major energy law to repeal PUHCA and decrease limitations on utility companies’ ability to merge or be owned by financial holding/non-utility companies. This led to a wave of mergers and consolidation within the utility industry.</td>
</tr>
<tr>
<td>2007</td>
<td>FERC issued Order 890, reforming the open-access regulations for electricity transmission, in order to strengthen non-discrimination in transmission services for alternative suppliers.</td>
</tr>
<tr>
<td>2008</td>
<td>FERC issued Order 719 to improve the competitiveness of the wholesale electricity markets in various ways, and to enhance the role of RTOs.</td>
</tr>
</tbody>
</table>

The role of the DSO is still being debated as well as the architecture. Generally, it is defined to be the entity which oversees operation of the distribution system, while additionally providing services to prosumers or demand-side services [RM14]. The DSO will become the interface between the bulk system operator (Balancing Authority, ISO/RTO) and the microgrid owners and operators (Prosumers). An evolution to an independent operator at the distribution level may lead to the emergence of a two market system. The wholesale market and retail market will be connected, but may be less dependent on each other, as the retail market facilitates transactions among microgrids and prosumers. Fig. 1.10 shows the bulk power system and wholesale markets at the top of the
The main reason for the emergence of DSOs is to create a network that can manage the interaction of microgrids with the main grid [Par16]. As more microgrids and prosumers emerge that want to buy and sell their own generation or have a degree of isolation from the main grid, it will become more and more difficult for existing distribution networks to manage the energy flow and ISOs to manage a more complex retail market. The DSO will provide reliability at the local level, reducing dependence on the ISO for grid balancing. The ability to isolate is protective. If the main grid is experiencing a fault, the distribution system can maintain its service, using its own local generation [Par16].

The DSO is a natural addition to the existing grid infrastructure. However, as will be discussed later, another system called The Energy Internet may be a more disruptive but efficient answer. As mentioned, ISOs and DSOs offer both grid operation and market functionalities [Par16]. Each of these roles can be developed separately or together. With increased isolation from the ISO, microgrids

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**Figure 1.9** Towards a Deregulated Power System [Ipa11]
must have enough reserve and flexibility to handle variable generation. Additionally, the DSO should provide measurements and forecasting to the ISO in order to manage power flow and coordination. The microgrids and prosumers making up a DSO may work together as an aggregate to bid into the wholesale market [Par16].

DSOs may have varying levels of autonomy. European DSOs are indirectly connected with bulk power and transmission service operators. They mainly operate distribution circuits and facilitate the customer’s choice of a primary energy provider, which they can choose in an open access system [RM14] [Eur]. The prosumers participate in the retail market independently of their DSO through their respective service provider. The service provider can interact with the bulk system as needed. The DSO, in this case, mainly controls operation of the grid, while linking to the retail market elsewhere [Eur].

In centralized models, the DSO operates directly with the ISO. However, without a wholesale market, the DSO relationship may just be with the balancing authority. Proposed variations of the DSO them are described below [RM14].
• Minimalist DSO - Would act as an aggregator of demand-side resources, probably based on conventional demand side programs and rates such as critical peak pricing and dynamic pricing. The DSO would be responsible for DER forecasts and expected responses to report to the ISO. The ISO may dispatch DERs directly through the DSO [RM14] Some challenges would be that the DERs would be scheduled without considering impacts on the distribution grid first, threatening reliability. Forecasting would be done from the bottom up, increasing accuracy, instead of the conventional way of starting at the top.

• Pseudo Balancing Area DSO - Would be identical to the Minimalist DSO, with additional responsibilities to control energy imbalances at the DSO level, including direct control of DERs and other dispatchable assets. The DSO will provide forecasting and make the DER capabilities known to the ISO, but will control individual assets that deter the aggregate, supporting reliability on the distribution grid [RM14].

• Comprehensive DSO - Would act as a market coordinator between DER asset operators (prosumers) and the ISO. Prosumers will offer capabilities to the DSO, which can then offer aggregate assets to the ISO. Here the DSO acts as a middle man in a deregulated market where the prosumers have buying and selling power besides conventional demand response programs and rates. The DSO may charge a fee to prosumers for this service and allocate charges based on performance and bids [RM14].

• Maximalist DSO - Would extend the Comprehensive DSO to include facilitation of a prosumer retail market. The DSO can buy DER and prosumer capabilities but will also facilitate bi-lateral arrangements among prosumers. This is often called the transactive energy model, as will be explained further later. The DSO will be responsible for secure and reliable distribution operation while supporting a retail transactive market [RM14].

As discussed in the Maximalist DSO model, the retail market at the DSO level should facilitate transactions between the prosumer and the DSO or just among prosumers. Transactions among prosumers is the concept behind The Energy Internet, as well as transactive energy. As mentioned in the discussion of DERs, prosumers should manage their resources so they can buy and sell at appropriate times, smoothing imbalances in their generation and load. Their distribution grid, or microgrid should be balanced locally if possible, to increase energy efficiency and reduce disturbances to the main grid caused by variable DERs. DSOs are a governing entity that will allow a growing population of prosumers, DERs, and microgrids to operate on the distributed grid while profiting from their demand-side assets.
Before energy transactions among prosumers are more broadly considered, let’s detail the current retail market for consumers and prosumers, within the framework of deregulation. Many residential customers sign up for a flat rate with their utility. This usually consists of a baseline charge per month plus a charge per kWh of energy consumed. However, in today’s evolving market, other types of programs are available that utilize the opportunity to affect the customer’s demand. Many customers do not desire to change their load, but prosumers have incentive to save more by adjusting their generation or utilizing energy storage. These types of programs fall under the heading of demand response.

There are two categories of demand response programs, called price-based demand response and incentive-based demand response. The difference is that price-based programs allow the prosumer to determine if they will change their consumption based on a price arrangement [Su14]. These types include

- **Real-time pricing (RTP)** - Dynamic prices that reflect the true cost of electricity on an hourly or half hour basis. These prices are based on wholesale spot markets, which reflect the real-time cost of electricity in the bulk power system

- **Time-of-use (TOU)** - A pricing structure determined by the utility ahead of time. Predefined peak and off-peak periods are established with corresponding rates [Su14]. The customer can knowingly consume with this structure in mind

- **Critical peak pricing (CPP)** - Similar to TOU, but critical peak hours are given higher prices, only a couple times a year [Su14]. The peak hours only happen during a small part of the time, but the time is determined by prices in the real-time spot market.

Incentive-based programs give consumers and prosumers less control, but can directly support the utility during times of need. In these programs, grid operators can directly control the loads of customers who have signed up to receive incentives for their participation [Su14]. These types include

- **Emergency demand response program (EDRP)** - A program for large energy users such as commercial and industrial customers to reduce their consumption during peak periods [Su14], as notified by the utility.

- **Direct Load Control (DLC)** - Utilities can remotely control residential loads such as air conditioners for contracted consumers in exchange for incentives [Su14]

- **Interruptible/curtailable rates** - Customers are notified on short term notice to reduce energy consumption or are temporarily cut off in order to maintain service for other grid customers
[Su14]. These customers are paid an incentive and the grid stays operational for the majority of other customers.

The overall impact of these pricing structures on energy markets and grid reliability still has to be determined as their popularity grow. For residential prosumers, price-based programs seem the most advantageous, especially if the program provides incentives for energy flow onto the grid. Currently, many prosumers have net-metering contracts, which allow them to "sell" their generation onto the grid by turning back the meter on their consumption for the month. More detailed programs are being proposed that would use one TOU scheme for consumption and a different one for generation.

As a point of reference, two TOU rates are shown below in Fig. 1.11 and Fig. 1.12.

![Figure 1.11 Southern Edison TOU rate](image)

The Southern Edison TOU rate in Fig. 1.11 applies to a particular load class (residential customers based off their average monthly load) and is broken into three pricing period. The price for each period is displayed according to a summer and winter season. Being in California, the on peak times (2 pm until 8 pm) correspond to the CAISO duck chart, where the peak in aggregate demand occurs before 9 pm.

The Duke Energy Progress TOU rate in Fig. 1.12 also breaks its rate into summer and winter seasons and three pricing categories. The hours are slightly different and the prices are less expensive, as the cost of electricity is cheaper in North Carolina. The prices are included in Table 1.2.
### Figure 1.12 Duke Energy Progress TOU rate

### Table 1.2 North Carolina - Schedule R-TOU, Prices

<table>
<thead>
<tr>
<th></th>
<th>Cooling Season</th>
<th>Warming Season</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Charges</strong></td>
<td><strong>On-peak</strong> $0.23264 per kWh**</td>
<td><strong>On-peak</strong> $0.20920 per kWh**</td>
</tr>
<tr>
<td><strong>Shoulder Peak</strong></td>
<td><strong>Shoulder Peak</strong> $0.11545 per kWh**</td>
<td><strong>Shoulder Peak</strong> $0.10958 per kWh**</td>
</tr>
<tr>
<td><strong>Off-peak</strong></td>
<td><strong>Off-peak</strong> $0.06520 per kWh**</td>
<td><strong>Off-peak</strong> $0.06520 per kWh**</td>
</tr>
</tbody>
</table>

### 1.3.3 Dynamic Pricing and Transactive Energy

The Real-time pricing (RTP), Time-of-use pricing (TOU) and Critical peak pricing (CPP) described in the previous section are all types of dynamic pricing [MR16], or a pricing scheme based on current market demands. Dynamic pricing varies according to what consumers are willing to pay. Dynamic pricing has been proposed as a control mechanism, [Kok11][PA15] giving prosumers agency to make decisions in the market rather than solely respond as customers in the one-directional legacy system. Integrating demand and supply flexibility into the operation of the electricity system allows for a more efficient market, predictable dynamic price response, and optimal utilization of distributed energy resources (DERs) [Kok11]. This process is referred to as transactive control [AN15][Gri]. Transactive control is a form of market-based control, that utilizes bi-directional communication to make energy transactions among distributed energy prosumers to create a stable, reliable grid. Transactive control is a mechanism for the Internet of Things or the Energy Internet, as will be
Dynamic pricing often refers to a rate, or pricing scheme, between the utility and the customer or prosumer. Transactive control can also describe this relationship, as a pricing mechanism is used to control the behavior of devices on the grid. However, it more commonly refers to an energy management scheme where the price is determined by a two-way bidding or negotiation among
the buyer and seller or the buyer and market coordinator.

In the previous section, types of demand response programs were discussed, many of which included rate structures dependent on dynamic pricing. In Fig. 1.13 energy management approaches will be discussed at the distribution level. In order to understand transactive control, other energy management techniques must be discussed as a point of reference. Techniques that include dynamic pricing and demand response will be indicated.

As shown in Fig. 1.13, four general classes of energy management approaches for distributed grids are: Top-Down Switching, Centralized Optimization, Price Reaction, and Transactive Control [KW16]. These classes are determined by whether they utilize one-way or two-way communications and if energy decisions are made centrally or locally.

- **Top-Down Switching** - Consists of classic demand-response programs where a broadcast signal switches a device on or off. In this case, the energy decision was made centrally and dispatched through one-way communications to the device. The incentive-based programs mentioned in the previous section fall into this category.

- **Centralized Optimization** - Energy management decisions are made centrally but the central controller receives information from the devices. Decisions are made centrally, but two-way communications are used. Based on available information and global and local control goals the controller can optimize for the best solution for the entire system, and then dispatch commands to the devices [KW16].

- **Price Reaction** - This category includes price-based demand response and dynamic pricing. A price signal is sent to end users and devices via one-way communications and the energy decisions are made locally by the end users with the price in mind. In most cases, a new energy price will be sent automatically to energy users at specific time intervals [KW16]. However, TOU rates could qualify as a rudimentary price-reactive system.

- **Transactive Control** - End users, microgrids, devices participate in an automated market with representation from the bulk power system at the distribution system level. Two-way communication is used to determine prices and energy transactions [KW16]. Like the price reaction class, transactive control allows devices to respond to prices optimally via a local intelligent controller or agent. However, the two vary, because the agent communicates preferences and bids into the market before the transaction takes place [KW16].

As a summary, Top-Down Switching is criticized ignoring the consumer altogether and interferes with their autonomy and preferences. While simple to implement, it does not utilize the potential of
all devices as their states are unknown. Centralized Optimization can fully utilize all devices and predict the reaction of the system but raises major privacy issues in that the states of the devices and end user info is known to the central controller. Further, any changes in the system must be constantly updated. The Price Reaction class has gives the devices full potential to respond, if they chose to do so locally and eliminates privacy issues. However, the collective reaction of all prosumers to the price signal is difficult to predict. Transactive control has all of the benefits lacking in the other classes. It has an efficient market, can predict the system reaction, allows full response of devices, and protects privacy [KW16]. All of these management systems require controllers and advanced optimization, whether they are located centrally or locally. The classes with one-way communications have a slight advantage in that their control strategy is not as complex.

Transactive energy systems have been implemented through various demonstration projects in the U.S. and Europe. Some of these projects were the Olympic Peninsula Demonstration (2006-2007), the AEP Ohio gridSMART Real-Time Pricing Demonstration (2010-2014), the Pacific Northwest Smart Grid Demonstration (2010-2015), and Couperus Smart Grid (2011-2015). The overall results indicated reliability and economic benefits. Automation was key in the demonstrations so that little user input was required to monitor the system. More data is needed to analyze algorithm learning patterns over a long period and additional models to test and explain the architecture and results are necessary. Many demonstrations focused on specific household loads. As distributed PV generation and home energy storage become more prevalent, the results may change.

1.4 Microgrid Control

There is an established hierarchical structure to microgrid control that exists in three stages: primary control, secondary control, and tertiary control. Prosumers may own and operate their own microgrid or be a part of one. The highest level of control considers operation of the microgrid, as energy management, and could be utilized as transactive control. To understand how the structure fits together a review of definitions is explained below.

• Primary Control - Stabilizes voltage and frequency, including after an islanding event or power outage. Provides plug and play capability for DERs and other devices. Mitigates circulating currents that can cause over-current events and damage devices. The primary control provides voltage and current references for DER control loops [BD12]

• Secondary Control - A centralized controller which restores voltage and frequency deviations caused by primary control. The secondary loop has a slower response than the primary control loop [BD12]. This loop can be referred to as power management.
• Tertiary Control - The last and slowest control level. Tertiary control determines the power flow between the microgrid and main grid, therefore performing energy management. The economics of energy transfer to and from the main grid play a role in determining the optimal operation of the microgrid [BD12]. The state of charge or health of the battery energy storage system or available PV, and controllable loads can also play a role. If prices or economic contracts are negotiated between the microgrid and the main grid to determine power flow [AN15], then transactive control is happening during this stage as well.

As seen in Fig. 1.14 the line between grid reliability and economics becomes blurred between the one minute and five minute mark. There are not many systems in which the variable cost of a good is so intimately entwined in it's production and secure delivery. Transactive control is unique in that it uses economics to affect the quantity and ultimately reliability of power produced. The legacy system could easily separate power management and ancillary services from economics and long-term energy use. However, as distributed generation and DERs become more prevalent, the balancing authority for the distribution grid will become more rooted in device management. The same devices and sources will work together to provide grid balancing, power, and energy management, instead of just one or the other.

**Figure 1.14** Where Reliability and Economics Intersect [Ipa11]
1.5 The Concept of the Energy Internet

The Energy Internet is a system where energy can be requested and sent from anyone, anywhere, at any time [HU16]. In the digital age, such a system could be invented that is decentralized, efficient, and reliable [Rif]. Many researchers are developing software to meet those goals, like the demonstration projects discussed in the previous section to study transactive energy. ARPA-E funded a project at Georgia Tech to develop such an energy internet for the smart grid. The Green Electricity Network Integration (GENI) project was founded there to "develop and demonstrate an internet-like, autonomous cyber-physical distributed architecture for the electric power grid" [Gte].

The Energy Internet is proposed to enable prosumers to compete with each other in a deregulated market via a consumer-to-consumer commerce model, similar to eBay [Su14][SH13]. It bypasses the hierarchical structure proposed by DSOs and ISOs to create a decentralized market, where every player is a peer interacting with other peers. Like eBay, other companies like AirBnb and Uber have disrupted the current market system by creating an alternate one, in which buyers and sellers can directly sell to each other, without a middle-man. In the case of Uber, smart algorithms pair a taxi driver with a passenger. Frequency based pricing could be used as a parameter to determine autonomous energy pricing in an Uber-like peer-to-peer system. In a smart, automated system, a prosumer’s transactions will be made in moments. The Energy Internet will match a prosumer’s offer with a willing customer, automatically.

All the components of such a system are depicted in Fig. 1.15. The Energy Internet is often compared to the changes underwent by the computer industry in the 1980s and 1990s [Hua10]. An industry of centralized computer mainframes transitioned to a client-based distributed infrastructure networked via the internet. Such a paradigm shift might be necessary to switch from a fossil fuel based energy grid to one in which renewable energy is the main source.

1.5.1 Required Technologies

In order to make the transition to The Energy Internet, three technologies are key. They are often compared to their computer industry analogs [Hua10]. First, a plug-and-play interface is needed, similar to the RJ45 Ethernet interface. This allows any device to be instantly connected and recognized by the grid. As more devices are developing smart capabilities, the network of all of them is being referred to as the Internet of Things. Besides traditional grid devices, the Internet of Things applies to other physical devices like vehicles, buildings and household loads, which are connected through their electronics, software, sensors, and network connectivity. Second, an energy router is necessary to route information and energy between devices. Last, an open-standard operating
system is needed like TCP/IP and HTML to utilize the communication network and coordinate system management with energy routers.

FREEDM at NCSU has developed a resilient infrastructure which will hopefully be implemented in the future grid as a key enabler of The Energy Internet. As shown in Fig. 1.16, the three key technologies connect DERs to the main grid. A solid state transformer (SST) is a physical node which supports an AC or DC medium voltage grid connected to an AC and/or DC microgrid. This microgrid can be referred to as an energy cell. Each prosumer may own and operate one of these cells or multiple prosumers may be connected to one cell. The devices in the cell, like energy storage, load, and distributed generation all have the proposed plug-and-play capability. The SST itself fulfills a variety of roles, providing isolation between the grids, managing energy and power flow, and communicating between devices and grids as an energy router, the second key technology. Lastly, distributed grid intelligence software (DGI) can be housed in the SST and communicate among devices while directing energy transactions through the SST as the third technology. Fault isolation devices (FIDs) are also necessary as protection for the system, which can operate as many connected nodes, or be islanded when necessary. The SST in particular will be a focus in Chapter 3.
1.5.2 Zero Marginal Cost Society

A marginal cost is the cost added by producing one extra item of a product. In terms of energy, it does not refer to the fixed cost of a generation plant, for example, but to the variable cost to generate one extra unit of electricity. Jeremy Rifkin author of "The Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism" argues that business operators are always trying to reduce the marginal costs of their products so they can gain more profit. He argues that technology is becoming so powerful and productive, that marginal costs may be reduced to near zero, making goods and services essentially free [Rif]. The greatest example of this so far has been with the online media industry. As cellphones, tablets, and computers became more widely used, the cost to communicate and share information has reached almost zero. Anyone can create their own video or blog on the internet and share it freely with everyone else. Consumers of magazines, newspapers, and online media are no longer willing to pay for these services, as there are so many alternatives. Consumers are easily distracted with so many free information sources competing for their attention. Rifkin argues that the zero marginal cost phenomenon in online media will reach physical good and services via the Internet of Things. With so many goods being tracked by sensors, people and things will become connected in a lateral neural network. Three operating systems will make up the network: a communication, an energy, and a logistics internet.
The future of energy, especially renewables and energy storage, fit into this imagined society because their marginal cost is already near zero. Installed solar PV or wind has a fixed cost, but no variable or fuel costs to produce electricity. Energy storage also has a fixed cost and a limited lifecycle, but it’s marginal cost to charge and discharge is very low. Capitalism will drive prices lower as DERs start to become more competitive than conventional sources. Since distributed generation systems are smaller than conventional power plants, they win in terms of fixed costs as well. With the communication infrastructure of The Energy Internet, prosumers will be able to trade energy at very little cost. As capitalism drives costs to zero, Rifkin predicts a new system will take it’s place, called the Collective Commons [Rif]. Such a peer-to-peer economic model is also being called the sharing economy. Technology such as blockchain is being created to manufacture trust in such a network. Our commerce and energy system is on the path to decentralization and democratization, according to thought leaders and projects in the space, through concepts like Bit-Energy [Luo17] and the Brooklyn Microgrid project [Bro] and Energy Web Foundation [Ewf].

1.6 Proposed Pricing Scheme and Contribution

This thesis proposes a bi-directional rate, falling under the RTP category based on the grid frequency. A TOU rate provides a charge for energy used, while a RTP rate reflects the cost of grid balancing. A rate that combines the advantages of both would be advantageous for prosumers and the grid, as seen in Chapter 4.

The frequency based real-time pricing scheme proposed in this thesis is a dynamic price. It falls between the classes of price reaction and transactive control. Traditionally, reading the frequency to determine a price for a prosumer is purely reactive and requires one-way communication to the prosumer. The decision occurs on the local level. However, if the prosumer is providing frequency regulation in their response to the price (which could also be termed as an ancillary service), then there is some feedback to the main grid in terms of the grid frequency. In terms of transactive control, a bidding market is not part of the scheme. However, there is autonomous feedback that should reduce uncertainty in the system reaction. The next price signal will be determined by the response to the previous one, providing a control feedback loop. The time interval proposed for the pricing scheme or rate is the one minute mark and five minute mark, as will be discussed in the next chapters.

As mentioned, frequency based pricing is an autonomous control loop in this thesis, and a form of price reactive energy management. It does not directly contribute to models of bidding and market clearing among prosumers, often referred to when discussing transactive energy and the
peer-to-peer Energy Internet. However, frequency-based pricing simulates the type of variable and unpredictable mismatch of supply and demand in a free, transactive market. Like the grid frequency, the cost of good and services in The Energy Internet will fluctuate and prosumers will act accordingly to optimize their transactions, contributing to system equilibrium. Still, the grid frequency is a sensor for grid balancing. Autonomous control of grid frequency through prosumer transactions is a critical requirement of The Energy Internet. Here, a frequency based price is proposed.

1.7 Outline

Chapter 2 will introduce a dynamic, frequency-based price. This frequency based price will be designed for frequency regulation at the five minute interval. Methodology for determining the price and determining a prosumer’s response to the price will be discussed.

Chapter 3 will discuss the market structure and enabling technology required to implement a frequency-based price. A day-ahead schedule and real-time adjustment will be proposed for prosumers to emulate the market structure in ISOs at the bulk power level. The Solid State Transformer (SST) will be discussed as the energy router for the smart grid, an enabling technology for frequency based pricing. Experimental results from an SST enabled microgrid will be shared.

Chapter 4 will introduce a single direction frequency based real-time electricity rate, based on a hybrid structure. The hybrid structure will support participation in the day-ahead and real-time market by combining a time-of-use (TOU) pricing scheme with a real-time frequency based price. The simulation results for a few model homes will be discussed.

Chapter 5 will expand upon the linear programming model to simulate results for two-way power flow. The frequency based rate design will be analyzed, along with the frequency variation for five days and cost to ESS model. The daily energy bills for four home types will be discussed: a home with load, PV, and ESS, a home with load and ESS, a home with load and PV, and a home with load only. The final savings for homes with ESS will be presented in this discussion.

Chapter 6 will be the conclusion and the future work.
2.1 Motivation

In this work, an electricity rate is proposed for prosumers based on the grid frequency, in real-time, measured every five minutes in this chapter. Such a rate is dynamic and transactive, creating a market for distributed energy storage through economic incentives. With increased uptake of variable distributed generation (DG), additional energy storage systems (ESS) will be required to store excess energy for periods of high load, low generation. ESS could be provided by the utility, but distributed, local, ESS would be a better match for DG, when considering efficiency, reliability, and required infrastructure. In return, distributed ESS will help the utility or grid balancing authority match the supply and demand on the grid, through frequency regulation and other services.

Through a frequency-based electricity rate, prosumers will be encouraged to purchase ESS to offset their own or their neighbor’s renewable DG, such as solar. This pricing scheme and thesis considers the variable part of the electricity bill only, as an incentive to influence prosumer behavior and provide opportunities for prosumers to behave as "Citizen Utilities" [GN17]. Other fixed costs may be needed to offset utility expenses, such as line costs, metering, and connection fees and are not considered in this work and may be analyzed during other comprehensive cost/benefit projects.
Why frequency based pricing?

1. Generation and loads can respond in real-time and provide frequency regulation as an ancillary service
2. Does not require communication with other devices to determine a price
3. Directly responds to the needs of the utility or balancing authority faster than other real-time pricing schemes (which operate on a 15 min or hour time scale)
4. There is motivation for prosumers to purchase energy storage or change their consumption in order to smooth frequency deviations in the grid and balance their own mismatch in supply and demand
   
   For example, a prosumer may curtail or store renewable generation that would otherwise be injected onto the grid at an inopportune time as a reaction to a frequency based real-time price.
5. Time Of Use (TOU) prices or a day-ahead pricing schedule can also play a role in a hybrid scheme to establish a baseline price and reflect the cost of the energy being generated.

2.2 Background

2.2.1 Prior Art

As DERs increase, frequency regulation will become an important grid service. As contributors to the variability of power flow on the grid, prosumers should have a role in controlling the grid frequency, as an ancillary service. New technical standards, operational protocols and market rules are needed in order for microgrids to be implemented in the future power system [Tee14]. In order for microgrids to function autonomously, a control mechanism analogous to the conventional frequency droop response of synchronous generators needs to be applied to the power electronics that interface DERs with the grid [Tee14]. The grid frequency can be used as a droop control for microgrids [Kaf16]. A solid state synchronous machine has also been proposed to take the place of the conventional generator [Yizhe16]. System frequency elasticity has been defined along with a price droop signal in order to adjust the sensitivity of DER response to changes in the system frequency [Tee14]. These methods focus on primary frequency control. This work demonstrates frequency based pricing for secondary frequency control and energy management. Frequency based pricing will occur within the one minute to five minute time frame.

In terms of frequency regulation, previous work has shown that prosumers can bring frequency deviations back to their nominal values after small perturbations [Naz14]. A successful framework
has been proposed for distributed frequency regulation in prosumer-based electricity systems [Naz14]. The monetization of such a framework needs to be developed. Traditionally, ancillary services have been compensated via capacity payments or performance-based payments [PA14]. A price-based operation has been suggested to reduce frequency deviations and coordinate non-cooperative energy player's participation [Jin13]. This control rule is based mostly in ISO connected power grids, without much consideration for prosumers and DERs. From a control prospective, it is easier to coordinate devices and compensate them later. However, a frequency based price, engages prosumers and encourages competition and a free market. As mentioned, a real-time frequency based price will also influence penetration levels of DERs on the grid and encourage more balanced participation. As described, price based frequency control is being explored at the system level [Jin13][Naz14][Tee14]. This work focuses on the price impact for prosumers and costs for energy storage, but more system demonstrations are needed. The PowerMatcher is a demand side management software which has been developed to coordinate energy transactions for prosumers, including frequency support based on local frequency measurements, influencing the energy price [Sye15]. More simulation results will be helpful to determine the resulting prosumer energy bills and grid stability.

There are some concerns that price-reactive control and demand response programs may be a challenge to system operators as the system response of thousands or millions of unknown devices will be difficult to predict. Further, a price-based signal might result in spontaneous oscillations as devices overcompensate for small frequency deviations, achieving the opposite of the desired frequency restoration objective [CH11]. For example, widespread use of TOU rates can have the unintended effect of creating large demand spikes following an on-peak period as devices are scheduled to operate during off-peak hours. A Multi-TOU and Multi-CPP price structure have been developed to coordinate customers so that each is assigned to one of several TOU rates with varying on-peak hours [MR16]. However, these studies focus primarily on load response. This thesis will consider control of energy storage and possible PV curtailment, while maintaining a desired load. With these additional sources of flexibility, prosumers have greater power and influence. Within the energy management time scale of one to five minutes, intelligent algorithms will reduce hard to predict consumer behavior. Price response forecasts and coordinated efforts among utilities and devices are also possible [CH11]. Additional studies are needed, but response to frequency deviations will be possible autonomously, as prosumer behavior will be the main cause of frequency deviations in a high DER, future smart grid.

Previous work has focused on primary frequency support. Coordination with AGC signals has been considered [Tee14][Naz14] but the focus has been the response to a frequency disturbance instead of frequency deviations from normal operation. [Yan16] has developed optimal scheduling
for ESS based on existing AGC signals and markets, but does not consider future markets for high DERs. This work extends the research to cover frequency based pricing for secondary frequency control as a transactive control mechanism for residential prosumers.

Using frequency to generate a real-time price is an easy way to simulate what a future transactive price may look like for a prosumer. In practice, it is an autonomous signal that can be measured by the prosumer at their location and requires no communications with other devices [Ham16]. Energy negotiations in a transactive market, may result in bidding that determines a stock market price. The grid frequency is equivalent to that model in that supply and demand of energy drive the grid frequency, which can be controlled by the market price.

2.2.2 What is a Prosumer?

A prosumer can be an ISO, a utility, a microgrid, a commercial building, or a residential home [Naz14]. A prosumer is a consumer of electricity and a producer of electricity. They will have physical energy devices like loads, renewable generation, energy storage, and electric vehicles. A control and communication layer will connect to most of these devices (as explained in the Internet of Things) [Naz14]. Prosumers will be connected in a coordinated framework with the utility, DSO, ISO, and/or other prosumers. In this work, a single residential prosumer is the main focus.

As shown in Fig. 2.1, a prosumer can make up its own microgrid or Energy Cell, meaning that one entity owns all of the devices behind the meter. The Solid State Transformer (SST) connects the prosumer to the grid, measures the grid frequency, and provides isolation, power flow, and voltage regulation. The "meter" lies above the SST at the AC connection to the main grid. The prosumer includes a residential load, distributed PV generation, and energy storage, referred to as a Distributed Energy Storage Device (DESD) in Fig. 2.1 and in this chapter but is called an energy storage system (ESS) elsewhere in this thesis. The two terms are equivalent in this work. In Fig. 2.1, the loads can be connected to a DC or AC bus.

\[ P_{\text{Grid}}(t) = P_{\text{DESD}}(t) + P_{\text{Load}}(t) - P_{\text{PV}}(t) \]  

(2.1)

The power flowing through the SST, \( R_{\text{Grid}}(t) \), must be balanced at all times, as shown in equation 2.1 for the residential prosumer.

2.3 Frequency Data

Frequency data was collected from the U.K. national grid status, available at [Ukd] in five minute intervals. The nominal frequency in the U.K. is 50 Hz. Additionally, PV data from a rooftop array in
Figure 2.1 Prosumer as an Energy Cell

Raleigh, NC and a simulated household load were obtained in five minute increments. These three inputs can be seen in Fig. 2.2. A one minute data set was used in Chapter 4, and the results between the two time intervals and data sources can be compared there.

The spectrum of common frequency values of the U.K. grid was plotted in Fig. 2.3. There was some inconsistency in the number of values falling in the normal frequency deviation range, with more values found \([49.97-49.98]\) and \([50.02-50.03]\) than in \([50.01-50.02]\), which falls within the normal range. However, the far ends of the frequency spectrum did not exceed the range of governor response into forced load shedding or tripped generation.

2.4 Pricing Scheme

After careful observation of the grid frequency data, a deadband pricing scheme was designed based on the general range of the TOU rates published in [Hoo14]. In Fig. 2.4, the deadband price curve and its linear variation intersect at \((50 \text{ Hz}, 0.033 \$/\text{kWh})\). The 0.033 \$/kWh price corresponds to the off-peak price in [Hoo14]. The maximum price for the linear price curve just exceeds the on-peak
Figure 2.2 Solar (PV), Load, and Frequency curves for one day, 5 min data

Figure 2.3 Frequency Spectrum UK, 5 min data
price of 0.171 $/kWh. The absolute maximum and minimum prices are set at 0.6 $/kWh and -0.6 $/kWh, respectively, for both curve types, as shown by the deadband price curve. This price design allows the utility to charge a low rate for power consumed at normal frequency and creates a cap for the maximum charge allowed, protecting the utility and consumer from extreme power charges.

As a result, the upper and lower frequency sections of the price curve are calculated according to

\[ Price(t) = x_1(frequency(t) - f_t) + C_d \]  

where \( f_t \) is the relevant deadband frequency threshold, \( C_d \) is the deadband price, and \( x_1 \) is the slope parameter. As mentioned, the limits of the price curve are constrained at \( \{C_{min} < Price(t) < C_{max}\} \).

The proposed pricing scheme features positive and negative market prices. A positive price of 0.07 $/kWh, for example, indicates that the utility will charge the consumer for power at this rate. A prosumer may also decide to sell power to the utility at this rate. At 0.07 $/kWh, the utility will pay the prosumer for the injected power. The positive price encourages upward frequency regulation, by creating an incentive for less consumption and more power injection. Conversely, a negative price of -0.06 $/kWh, for example, indicates that the utility will pay the consumer for power consumption. At the same time, a prosumer who wants to sell power to the grid, must pay the utility to inject power. The negative price encourages downward frequency regulation, by creating an incentive for more
consumption and less power injection. The design of positive and negative prices allows the utility to have greater influence on consumer and prosumer behavior, while keeping the cost of energy low for consumers without generation or storage and creating greater savings for prosumers that do.

### 2.5 Prosumer Response

![Prosumer Response, DESD Power vs. Price](image)

In response to the frequency based price curve, the SST enabled prosumer must determine its operation and optimize for economics. The prosumer will be billed according to its $P_{Grid}(t)$, which is defined in Equation 2.1. For this prosumer and many others, the load will operate as given, the Distributed Energy Storage Device (DESD) will charge and discharge as needed, and the PV can be curtailed.

The DESD response curve is calculated very similarly to the price curve (Fig. 2.5)

$$P_{DESD}(t) = (P_{lim} - P_d) \frac{Price(t) - C_{ct}}{C_{ct} - C_{dt}} + P_{lim}$$  \hspace{1cm} (2.3)

where $P_{lim}$ is the charge or discharge power limit, $P_d$ is the deadband power, $C_{ct}$ is the maximum charging or discharging price threshold, and $C_{dt}$ is the relevant deadband price threshold. The
response is calculated once for charging and once for discharging, as was the price for upper and lower frequency. The limits of the power curve were constrained at \( \{-P_{lim} < P_{DESD}(t) < P_{lim}\} \), where \( P_{lim} = 1.5 \text{ kW} \) and the state of charge (SOC) limits for the DESD were constrained at \( \{0.3 < SOC < 0.7\} \) with an initial SOC at 0.4.

### 2.5.1 Simulation Results

The deadband and maximum charging and discharging price thresholds were designed to optimize \( P_{DESD}(t) \). Generally, charging should happen at negative prices (the utility pays the prosumer to charge) and the prosumer should charge any unused PV or curtail it. Discharging should happen at positive prices (the utility pays the prosumer to discharge) and the prosumer should limit its grid consumption. As the price increases, the level of discharging should increase \( (P_{DESD}(t) \) becomes more negative) in proportion to the price. However, at a certain threshold price, \( C_{ct} \), the prosumer would want to discharge as much as possible, at its \( P_{lim} \). The response curve deadband may prevent draining DESD capacity before the most profitable time. For example, the price curve deadband, \( C_d = 0.033 \text{ \$/kWh} \), causes many frequency values to yield that price. In most cases, it is profitable to eliminate discharging during that frequency range, \( f_t \).

Solar was curtailed if the price was negative and \( P_{Grid}(t) \) was negative, meaning that the prosumer was paying to inject power onto the grid. In that case, \( P_{PV}(t) \) was decreased (after \( P_{DESD}(t) \) was optimized to charge) until \( P_{Grid}(t) \) was zero.

Table 2.1 lists several results after optimizing for various parameters of the price and response curves for the residential prosumer. As \( x_1 \) becomes more negative, the load cost tends to decrease and the algorithm savings increase. As the price curve frequency deadband, \( f_{deadband} \), narrows, savings tend to increase since there are more times available to charge and discharge. While it makes sense to operate the DESD at full \( P_{lim} \) only during times of high and low price, the results show that often it is profitable to operate at \( P_{lim} \) during every charge and discharge. It can be more economical to react to every shift in frequency, rather than waiting for the boundary values, since periods of charging and discharging closely follow each other in this frequency based pricing scheme. When proportional charging and discharging is more economical, the charging price threshold \( C_{ct} \) can be adjusted to find the optimum. The consumer is likely to favor high savings and low load cost, while the utility favors a higher final price and load cost. The third and seventh rows in Table 2.1 are good common ground solutions. The SOC plot of these solutions is found in Fig. 2.6.

Other parameters were adjusted during the simulation, such as discharging to provide for the load or charging to prevent solar injections, but these additions had little positive effect on the final results. Simulations with a larger dataset are needed to confidently recognize patterns in the data.
<table>
<thead>
<tr>
<th>$f_{\text{deadband}} = [50]$ (linear)</th>
<th>Load Cost</th>
<th>Load with PV</th>
<th>Final Price with DESD &amp; ED</th>
<th>Algorithm Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1 = -7$</td>
<td>0.2457</td>
<td>0.2035</td>
<td>-7.5244</td>
<td>7.7279</td>
</tr>
<tr>
<td>$C_{ct} = \pm 0.11$</td>
<td>with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{DESD}(t) = P_{lim}$</td>
<td>0.2457</td>
<td>0.2035</td>
<td>-7.4132</td>
<td>7.6166</td>
</tr>
<tr>
<td>$f_{\text{deadband}} = [50]$ (linear)</td>
<td>0.5877</td>
<td>0.3252</td>
<td>-1.5480</td>
<td>1.8732</td>
</tr>
<tr>
<td>$x_1 = -2$</td>
<td>with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{ct} = \pm 0.10$</td>
<td>$P_{DESD}(t) = P_{lim}$</td>
<td>0.5877</td>
<td>0.3252</td>
<td>-1.9602</td>
</tr>
<tr>
<td>$f_{\text{deadband}} = [49.97 - 50.03]$</td>
<td>0.4562</td>
<td>0.2879</td>
<td>-2.3773</td>
<td>2.6652</td>
</tr>
<tr>
<td>$x_1 = -5$</td>
<td>with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{ct} = \pm 0.07$</td>
<td>$P_{DESD}(t) = P_{lim}$</td>
<td>0.4562</td>
<td>0.2879</td>
<td>-2.3430</td>
</tr>
<tr>
<td>$f_{\text{deadband}} = [49.93 - 50.07]$</td>
<td>0.6005</td>
<td>0.3302</td>
<td>-0.7542</td>
<td>1.0844</td>
</tr>
<tr>
<td>$x_1 = -7$</td>
<td>with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{ct} = \pm 0.10$</td>
<td>$P_{DESD}(t) = P_{lim}$</td>
<td>0.6005</td>
<td>0.3302</td>
<td>-0.6132</td>
</tr>
</tbody>
</table>
2.6 Conclusion

In this chapter, a dynamic, frequency based real-time electricity price was proposed, simulated, and optimized to determine a preliminary design for the bi-directional frequency based rate and prosumer response strategy. The relevant parameters were identified in the design of a frequency derived pricing curve and subsequent DESD response curve for economic dispatch. Operation of the $P_{DESD}(t)$ was optimized in order to trigger a $P_{Grid}(t)$ reference for an SST enabled prosumer. In this proposed system, energy transactions will be conducted autonomously in real-time while responding to deviations in the grid frequency, therefore providing price-reactive frequency regulation. As shown, frequency based pricing gives prosumers an opportunity to support the grid, while making a profit as an energy producer. The next chapters will consider appropriate prosumer savings and discuss an energy management framework for the future residential prosumer, as well as SST enabled control and cost to energy storage. Later, a frequency based hybrid rate will be introduced for single direction and bi-directional energy flow.
CHAPTER 3

MARKET STRUCTURE AND ENABLING TECHNOLOGY

3.1 Market Structure for Residential Prosumers

In the previous chapter, a dynamic frequency based price was simulated for a residential prosumer. As explained in the introduction, energy transactions occur during various time periods facilitated by ISOs in the bulk power system. Prosumers could operate purely as a frequency based ancillary service, but there will likely be other electricity based costs in the future smart grid. Frequency control is required in the seconds to minutes range, and the spot market operates in real-time, but other scheduled dispatch of energy is planned hours or days ahead. As will be discussed later, much of the bulk energy related costs are accounted for in flat or TOU rates. Fixed costs may be charged on top of the energy based rate.

The ISO led energy market is separated into various time intervals, as economics merge with reliability (see Fig. 1.14). Prosumers will likely follow the same structure, by forecasting, scheduling operations, and then dispatching and optimizing to prices in real-time [DL11]. The control diagram and framework is described next.
3.1.1 Proposed Day-Ahead Schedule and Real-time Adjustment

Fig. 3.1 proposes a day-ahead and real-time energy management framework for a residential prosumer. The prosumer’s response can be price-reactive with or without incentives to inject power onto the grid. In addition to dynamic, frequency based real-time rates, the same structure can be used for other types of dynamic rates as well as energy transactions and negotiations taking place among prosumers in The Energy Internet.

In this framework, the prosumer uses linear programming to make a scheduled $P_{grid}(t)$ reference based on it’s known TOU prices, initial SOC, and solar and load predictions for one day. As the day progresses, the prosumer calculates the real-time energy price by reading the grid frequency every one second and processing and averaging the data to determine the real-time price every one minute. The real-time price, which the prosumer will ultimately be billed for, is the frequency based price added to the existing TOU price for each minute. At one minute intervals, the prosumer measures its current energy storage state of charge (SOC), and current solar and load values, allowing for errors between the forecasted and actual amounts to be considered. After calculating the current real-time price and considering the SOC, load, and solar measurements, a new, updated $P_{grid}(t)$ reference is determined and implemented for the prosumer. Five minute intervals were used in the previous chapter, but new datasets introduced in the next chapter have allowed this work to optimize for a one minute frequency response.

Fig. 3.2 depicts an example of the prosumer energy management framework in action. At the beginning of the day, the prosumer considers the TOU rate for the entire day and schedules a planned SOC curve for the day. As the day progresses in real-time, the frequency based real-time
rate is measured and calculated and added to the known TOU rate. The prosumer must update their charging and discharging schedule, impacting their SOC curve to strategically reduce costs to their energy bill as opportunities are presented. Adjustments are made to the prosumer’s planned SOC for each minute according to the real-time rate combined with the known TOU price. The resulting SOC curve (on the right) for one day looks different from the starting SOC schedule (on the left). The prosumer can utilize different strategies to decide how they will respond to fluctuations in the real-time price.

3.2 Solid State Transformer (SST)

In terms of frequency based pricing, the Solid State Transformer (SST) is an enabling technology because it can control power flowing to and from a prosumer, allowing them to buy and sell energy. Load, generation, and storage can also be controlled independently, but SSTs allow them to make nodes within networks, providing isolation, islanding, voltage and power management. Additionally, SSTs measure the grid frequency. As an enabling technology, the SST for each prosumer can measure the frequency, determine the price, and then set the appropriate power flow reference according to a smart algorithm stored within the SST’s Distributed Grid Intelligence (DGI) node.
3.2.1 **SST as an Energy Router**

The various capabilities of the SST are shown in Fig. 3.3. Similar to Fig. 2.1, the SST is shown supporting a home, stationary energy storage device, electric vehicle, and solar generation. The SST connects this prosumer to the utility grid and houses communication software, which can be used to communicate with a higher network and also the supported devices. The capabilities are listed in three categories: fault management, power management, and energy management. Fault management allows SSTs to disconnect and reconnect and power management is extremely important in its support of islanding modes, bi-directional energy flow, dc microgrids, and control of customer voltage. The energy management capability gives the SST its name as an energy router. As an energy router of the smart grid, SST can control and dispatch energy from one prosumer to another. As seen later in this chapter, energy routing can be autonomously controlled through a DC voltage droop.

Fig. 3.4 shows the energy router concept, depicting two SST nodes, supporting two Energy Cells (and prosumers) each. By connecting to the transmission lines, the SSTs can route energy at medium voltages to each other. The amount of energy flowing onto the grid or into each Energy Cell is also

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**Figure 3.3 SST Capabilities**
controlled. With the right infrastructure, these energy transactions could also occur laterally among multiple nodes, through The Energy Internet. Various pricing schemes and transactions can be enabled with this smart transformer technology.

### 3.2.2 Power Flow Regulation

As briefly described, the microgrid bus voltage can be used to dispatch the energy storage device shown in Fig. 3.5. By this method, the SST enabled bus serves as a communication link as well as a power transmission link. Here, the SST serves as an Energy Router, directing power from one microgrid to another [Wan12]. This smart transformer capability allows the prosumers of one Energy Cell to buy power and sell power to other Energy Cell prosumers, enabled by their SSTs. In order to route energy, the SST must regulate power flow bi-directionally from the utility grid to its microgrid. As shown below, power flow regulation at the SST level has been developed and demonstrated. Smart algorithms for economic dispatch can be implemented as a power flow reference to the SST.

In Fig. 3.6, the control diagram for the SST power and voltage control loop is shown. The addition of the power loop enables power flow regulation. At the start, the power reference is compared to the measured power, \( P \). A proportional-integral (PI) controller with upper and lower limits determines the reference for the DC bus voltage control. Once the reference is set, current control is used to control the DC bus voltage, which communicates charging and discharging commands to the DESD via droop control.
Figure 3.5 SST Energy Router and the DC Microgrid Energy Cell Configuration, where the prosumer is the owner and operator of the Energy Cell.

Figure 3.6 Control Diagram for SST Power and Voltage Control Loop.

Droop control is detailed further in Fig. 3.7 and Fig. 3.8. According to the droop curve in Fig. 3.7, the battery can be charged and discharged according to the bus voltage. The DC/DC converter interface in the battery storage unit will generate current references for charging and discharging.
based on the curve. The zero current range from 375 to 385 V serves as standby region for protection and stability. The power rating of the storage determines the slope of the curve. The open loop test is also shown in Fig. 3.8. Here the DC bus voltage is changed to observe the performance of the DESD dispatch. The current is positive (discharging) when the DC voltage is in the lower range and negative (charging) when the DC voltage is in the upper range. This control method allows the SST

**Figure 3.7** Battery Droop Control

**Figure 3.8** Open Loop Test Results
to estimate the battery state of charge (SOC), based on coulomb counting.

### 3.2.3 Experimental Results

The SST enabled DC microgrid testbed pictured in Fig. 3.5 will be used to study this economic dispatch problem and demonstrate its implementation via SST’s autonomous and distributed control capability. It contains a lithium-ion battery based energy storage device, housed in an energy storage system developed in house. This Distributed Energy Storage Device (DESD) charges and discharges according to the DC bus voltage [Xue15]. A smart algorithm for economic dispatch is located in the SST. The SST will then set the reference for the SST DC bus voltage via a power flow regulation control loop. A programmable load device serves as the aggregate load, and represents the summation of generated PV power and demand for the Energy Cell.

![Figure 3.9 Demonstration Plan](image)

The detailed power schedule for the battery calculated from the economic dispatch algorithm was implemented in a 380 V DC SST enabled testbed. As described in the microgrid Energy Cell dispatch strategy, the desired battery power was achieved by setting the SST power reference and implementing power flow regulation on the DC bus [Ham15]. To demonstrate this concept, a fluctuating aggregate power curve was programmed into a DC Programmable Load (Fig. 3.5). The
Figure 3.10 Experimental Results

curve is shown in Fig. 3.9. For the first minute of operation, power flow regulation was demonstrated, as the grid power passing through the SST was held constant at 100 W. During this time, the battery balanced the power and was therefore autonomously controlled by the SST. The experimental results are shown in Fig. 3.10. After one minute of power flow regulation, various power reference values from the dispatch algorithm were implemented in the SST to show a variety of energy management cases, showcasing its Energy Router capability. As seen in Fig. 3.9, the grid power is regulated at a negative value around the two-minute mark, followed by regulation at zero power for a brief period. The battery current in Fig. 3.10 closely follows the expected battery power in Fig. 3.9. The DC voltage fluctuates within range to charge and discharge the battery according to droop control. Lastly, islanding is demonstrated in the last minute. If a fault occurs at the SST level, the grid voltage goes to zero, but the battery discharges to maintain the DC bus and satisfy the load.

3.3 Conclusion

In this chapter the market structure and energy management framework for prosumers was discussed. Additionally there was an overview of the SST and its functions and capabilities. The power
flow control capability of the SST was designed and demonstrated. Battery droop control was used to communicate charging and discharging through the DC bus voltage, implementing a smart algorithm to provide an optimal voltage reference. The SST provides this reference by directing power flow as an Energy Router, operating via autonomous and distributed control. This method of decentralized control reduces the need for complicated or potentially unreliable communication networks, while enabling prosumers to optimize their consumption and generation. Strategies for the real-time rate adjustment allow prosumers to determine a new SOC curve in real-time based on their planned SOC curve for energy storage according to the day-ahead TOU prices. Linear programming is used to plan for the day-ahead energy schedule.

In the next chapter, simulation results for a single direction frequency based and TOU hybrid electricity rate will be discussed. The parameters for the hybrid rate will be designed and load profiles for different homes will be considered.
4.1 Introduction

In this chapter, a hybrid TOU and frequency-based electricity rate will be introduced and simulated for a residential prosumer. Like Chapter 2, this chapter utilizes a frequency based rate but combines it with a TOU rate. As discussed in Chapter 3, the energy management framework for prosumers should follow a day-ahead schedule and real-time adjustment.

For prosumers, energy prices should not be based completely on the grid frequency, but also on the physical electricity bought and sold, which is reflected in a TOU or baseline rate. This method helps maintain a positive electricity price and reflects the summation of two price signals: one which is based on planned energy transactions or price schemes (TOU) and one based on variable fluctuation in price, due to changes of supply and demand in transactive markets and/or the measured grid frequency.

In the following optimization and simulation, a combined frequency and TOU rate is designed
based on the results from the rate parameters experimented with in Chapter 2. The datasets have been updated in this chapter to reflect load and PV data from real homes courtesy of Pecan Street Inc. Dataport. Frequency data from the U.S. was obtained with smaller time intervals than the U.K. data in Chapter 2, allowing this study to update pricing and respond to frequency deviations on the one minute time frame.

4.2 TOU+Freq Hybrid Rate

A TOU plus frequency (TOU+Freq) hybrid rate was constructed using a TOU rate plus a frequency based rate. Frequency data measured every 0.10 seconds was obtained from FNET through CURENT, the University of Tennessee, Knoxville, and Oak Ridge National Laboratory. From the data, a 60 second and a 5000 second moving average were calculated as shown in Fig. 4.1 and a price was assigned to each frequency calculation as shown in Fig. 4.2. A new average was calculated every one minute for a total of 1440 data points for one day. The baseline TOU price for the hybrid rate was based on TOU rates from Southern Edison (SE). With an off-peak rate of 0.12 $/kWh, the maximum and minimum thresholds for the frequency based price were set to $\pm 0.12$ $/kWh to maintain symmetry and prevent the total price from being negative. The price vs. frequency function in Fig. 4.2 is based on previous work in Chapter 2. The frequency based price parameters will be further explored in Chapter 5.

![Figure 4.1 Frequency moving average](image)

The two TOU+Freq rates were designed by adding the frequency based price to the TOU SE
baseline. One used the 60 second moving average and the other the 5000 second moving average. These two TOU+Freq rates were compared to three other commonly used rates: a flat rate, a TOU rate based from Duke Energy Progress (DEP), and the TOU SE based from Southern Edison. The TOU SE rate was chosen because it defined peak hours to be during the challenging early evening hours of the duck curve. The TOU DEP does not schedule it’s peak hours during this time, but has a shoulder category during May, when the load data was measured. For sake of comparison both TOU rates were designed to have the same peak and off-peak price. These rates are detailed in Table 4.1 and shown together in Fig. 4.3. For a flat, 1 kW daily load, all five rates are about the same: $4.80 for the Flat Rate, $4.08 for the TOU DEP, $5.12 for the TOU SE, $5.05 for the 5000 Second TOU+Freq

Table 4.1 Rates, price/kWh

<table>
<thead>
<tr>
<th>Rate</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Rate</td>
<td>$0.20</td>
</tr>
</tbody>
</table>
| TOU DEP            | Off-peak (8 p.m. - 11 a.m.): $0.12  
|                    | On-peak (1 p.m. - 6 p.m.): $0.28  
|                    | Shoulder: $0.22               |
| TOU SE             | Off-peak (10 p.m. - 8 a.m.): $0.12  
|                    | On-peak: $0.28                |
| 5000 Sec TOU+Freq  | TOU SE ± $0.12 max           |
| 60 Sec TOU+Freq    | TOU SE ± $0.12 max           |
rate, and $5.11 for the 60 Second TOU+FREQ rate.

4.3 Linear Programming Model

Linear Programming was used to solve for the lowest energy price to the prosumer, using a given rate, load curve, PV curve, and energy storage parameters [HB12]. Implementation of a hybrid TOU+FREQ rate is proposed according to Fig. 3.1 in Chapter 3, where linear programming would solve for the day-ahead schedule using the known TOU price and then a smart algorithm or artificial intelligence would measure the frequency and device parameters, determine the frequency based real-time price, and make adjustments to the day-ahead schedule. But in this chapter, linear programming was used to solve for the total TOU+FREQ rate (day-ahead plus real-time) in order to compare the optimal outcome with other rates (TOU and flat rate). Implementation of the TOU+FREQ rate would be expected to near the mathematical optimum. A diagram of the simulation set-up for this chapter is shown in Fig. 4.4 with the relevant inputs and outputs.

In Chapter 5, the linear programming method for the TOU+FREQ rate will be compared to more realistic solutions determined by the proposed prosumer energy framework model (Fig. 3.1)
that separates day-ahead energy scheduling via linear programming from the real-time adjustment determined by a strategic prosumer response method or smart algorithm.

The linear programming model is defined as, $\min \{ f^T x \}$, where the decision variables are $x = \{ P_{\text{grid}}(t), P_{\text{pvused}}(t), P_{\text{charge}}(t), P_{\text{discharge}}(t), SOC(t) \}$. The total cost of energy to the prosumer should be minimized for one day according to the objective function

$$\begin{align*}
\text{Min} \quad f &= \sum_{t=1}^{T} \tau C_{\text{grid}}(t) P_{\text{grid}}(t) + k(P_{\text{charge}}(t) + P_{\text{discharge}}(t)) \\
(4.1)
\end{align*}$$

For the equality constraints, the power balancing equation for the prosumer is

$$\begin{align*}
P_{\text{grid}}(t) &= P_{\text{load}}(t) - P_{\text{pvused}}(t) + P_{\text{charge}}(t) - P_{\text{discharge}}(t) \\
(4.2)
\end{align*}$$

and the SOC for the battery, housed as an Energy Storage System (ESS) is

$$\begin{align*}
SOC(t) &= SOC_i + \frac{\tau}{\text{cap}} \sum_{j=1}^{t} (P_{\text{charge}}(j) - P_{\text{discharge}}(j)) \\
(4.3)
\end{align*}$$

The inequality constraint is

$$P_{\text{pvused}}(t) \leq P_{\text{pv}}(t) \quad (4.4)$$

In (4.1), $\tau$ is the time in minutes (where $T$ is 1440 minutes in one day), $\tau$ is the time constant in
hours, $C_{grid}(t)$ is the cost of electricity (the electricity rate) in $$/kWh, and $P_{grid}(t)$ is the power in kW flowing through the meter, while $k$ is a constant in $$/kW to account for the cost to the lifetime of the battery, multiplied by the power in kW charging or discharging, $P_{charge}(t)$ and $P_{discharge}(t)$. The constant, $k$, was set to 0.0002 $$/kW, estimated from partial charges occurring in a 10 kWh ESS costing 200 $$/kWh with about 10,000 full cycles until failure. The number of cycles per depth of discharge is shown in Fig. 4.5 for Saft Batteries. The calculation for partial charging was determined in [Ke15].

![Figure 4.5 Saft Energy Storage Systems Cycle Life at 25 degrees Celsius and 70 % capacity at End of Life [Saf]

Equation (4.2) includes the load, $P_{load}(t)$ and PV generation, $P_{pv\text{used}}(t)$. In (4.3), $SOC_i$ is the initial SOC (at $t = 0$) measuring 0.3 and the cap is the capacity of the ESS at 10 kWh. As shown in (4.4), if excess PV power is generated, but cannot be stored or used, it is assumed to be curtailed or wasted in this formulation. The $P_{pv}(t)$ is the generation potential and $P_{pv\text{used}}(t)$ is the portion after curtailment.

The upper and lower bounds for each of the $x$ variables are defined in Table 4.2. There are no incentives to inject power onto the grid, so $P_{grid}(t)$ is defined as one directional power flow to the prosumer.
Table 4.2 Upper and Lower Bounds for Optimization Variables, in kW except for SOC (out of 1)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{grid}(t)$</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>$P_{pvused}(t)$</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>$P_{charge}(t)$</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>$P_{discharge}(t)$</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>$SOC(t)$</td>
<td>0.3</td>
<td>0.99</td>
</tr>
</tbody>
</table>

4.4 Single Direction Power Flow Results

Residential data from Pecan Street Inc. Dataport 2016 was used to analyze various home load and solar curves and to size energy storage for such homes. In Fig. 4.6, three houses (A, B, and C) were selected in order to compare different load patterns. This data was taken from three different homes, measured every one minute, all located in Austin, Texas, in May 2012. Each home has a corresponding PV generation curve for each day, but one curve was chosen as shown in Fig. 4.6, in order to compare the load types.

The PV generation was fairly similar between each house, as they are all located in Austin. As commonly cited in the solar industry [Mar16], two days for one house have more similar load curves than two different houses during the same day. House A has a night focus, House B has a day focus, and House C has a mostly equal, but day/evening focus pattern.

The lowest energy cost for each house was calculated according to each of the five rates using the linear programming model. The results are shown in Table 4.3. The energy cost was optimized so that the sum of the third and fourth columns were the lowest. The third column, the cost related to $P_{grid}(t)$, is the amount the prosumer owes to it’s local energy provider, while the fourth column, the cost to it’s Energy Storage System (ESS), is an internal cost to the prosumer. The focus of the simulation is to optimize for variable costs in order to study the effects of load patterns and rate structures on energy scheduling.

The total daily consumption was similar for each house. House A had a load of 23.04 kWh, House B a load of 24.07 kWh, and House C a load of 24.22 kWh, as is shown for the flat rate with House A having the lowest price for it’s load only. PV generation was 21.63 kWh. With the addition of PV, but still no ESS (the second column), House A became more expensive than the other houses. House B and C were able to utilize the majority of their PV generation because more of their energy
consumption occurred during the day. House A did not reduce its cost as much by adding PV because it had much less load that could be offset during PV generation. Adding ESS did help, as shown in the third column, but the benefits were much greater to the other two houses, who could store most of their excess solar in a 10 kWh battery ESS. House A would need a larger ESS to see these benefits.

The $P_{grid}(t)$ cost to the prosumer did not fluctuate between the TOU rates for House B and C. There was enough PV generation and ESS capacity during the peak and shoulder hours that the difference between these two rates did not affect the total cost to the prosumer.

By far, the TOU+Freq hybrid rates proved to be the most economical to all three houses. The advantage of such a dynamic rate is that high and low prices are distributed more evenly instead of being clumped together during peak and off-peak hours, allowing for more economical use of energy storage. The cost to ESS is slightly higher during the TOU+Freq rates than the other rates, as a result. Despite the increase of Cost to ESS, the 60 Second TOU+Freq rate is the most economical, charging $0.4096 to House B and $0.0687 to House C. The strength of this rate is that it can essentially lower the prosumer's bill to zero while providing one minute frequency regulation and maintaining smart use of energy storage.
Table 4.3 Energy Cost for One Day ($), Source: Pecan Street Inc. Dataport 2016

<table>
<thead>
<tr>
<th></th>
<th>Load Only</th>
<th>Load with PV</th>
<th>Pgrid: Load PV, ESS</th>
<th>Cost to ESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>House A</td>
<td>4.6084</td>
<td>3.6126</td>
<td>2.0497</td>
<td>0.1875</td>
</tr>
<tr>
<td>House B</td>
<td>4.8136</td>
<td>2.4129</td>
<td>0.8584</td>
<td>0.186</td>
</tr>
<tr>
<td>House C</td>
<td>4.8448</td>
<td>2.6534</td>
<td>0.9688</td>
<td>0.2021</td>
</tr>
<tr>
<td>TOU DEP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>House A</td>
<td>3.6045</td>
<td>2.4285</td>
<td>1.2305</td>
<td>0.1875</td>
</tr>
<tr>
<td>House B</td>
<td>4.8345</td>
<td>1.7662</td>
<td>0.515</td>
<td>0.186</td>
</tr>
<tr>
<td>House C</td>
<td>4.709</td>
<td>1.9684</td>
<td>0.5813</td>
<td>0.2021</td>
</tr>
<tr>
<td>TOU SE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>House A</td>
<td>5.0712</td>
<td>3.6787</td>
<td>1.4083</td>
<td>0.1999</td>
</tr>
<tr>
<td>House B</td>
<td>5.7746</td>
<td>2.4152</td>
<td>0.515</td>
<td>0.2182</td>
</tr>
<tr>
<td>House C</td>
<td>5.8769</td>
<td>2.8105</td>
<td>0.5813</td>
<td>0.2289</td>
</tr>
<tr>
<td>5000 Sec TOU+Freq</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>House A</td>
<td>5.2043</td>
<td>3.6839</td>
<td>1.0847</td>
<td>0.2739</td>
</tr>
<tr>
<td>House B</td>
<td>6.0999</td>
<td>2.4282</td>
<td>0.1835</td>
<td>0.2555</td>
</tr>
<tr>
<td>House C</td>
<td>6.0755</td>
<td>2.7312</td>
<td>0.1962</td>
<td>0.2837</td>
</tr>
<tr>
<td>60 Sec TOU+Freq</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>House A</td>
<td>5.1859</td>
<td>3.7267</td>
<td>0.6837</td>
<td>0.337</td>
</tr>
<tr>
<td>House B</td>
<td>5.956</td>
<td>2.4646</td>
<td>0.0496</td>
<td>0.2729</td>
</tr>
<tr>
<td>House C</td>
<td>5.9958</td>
<td>2.7984</td>
<td>0.0687</td>
<td>0.3028</td>
</tr>
</tbody>
</table>

The SOC is plotted for each of the Houses. House A is Fig. 4.7, House B is Fig. 4.8 and House C is Fig. 4.9. In Fig. 4.9, the SOC is plotted for House C for each of the rates. Compared to the TOU and flat rates, the TOU+Freq rates encourage the ESS to charge and discharge during the morning, increasing the time it is used for the day, and lowering the total energy cost to the prosumer. There are two 60 Second TOU+Freq rates graphed in Fig. 4.9. The first, f1, is the 60 Second TOU+Freq rate graphed previously. The second, f2, uses frequency data from the following day. Unlike the other rates, the f2 rate requires less charging during the second half of the day for House C (Fig. 4.9), possibly indicating that a smaller ESS could be used for single direction power flow.

The SOC curve for House A is very similar to House C, but it still reaches full charge for the frequency curve for day 2. Since its load peaks in the evening, it must store as much energy as possible to save during the peak hours. House C has load throughout the afternoon, which is still the peak time, so it uses its PV to offset the load and does not need to store as much. House B also
has load during the day, but does not need to fully charge with its PV generation. At 6 PM, though, its load drops to nearly zero and its excess PV is stored for later in the evening. Frequency support
mostly provided in the mornings for these houses, as their SOC curves do not vary from the TOU rate in the afternoon and evening timeframe.

4.4.1 Two Different Days of Frequency Data

The energy prices using a second frequency curve for the 60 Second TOU+Freq rate are similar: $0.5089 for House A, $0.131 for House B, and $0.1567 for House C. These energy bills and the ones for the 5000 Second TOU+Freq rate are shown in Table 4.4. The TOU+Freq rates for the two days are shown in Fig. 4.10 for the first day and Fig. 4.11 for the second day.

<table>
<thead>
<tr>
<th>Time (1 min data)</th>
<th>SOC (out of 1)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12AM</td>
<td>0.6837</td>
<td>0.0496</td>
</tr>
<tr>
<td>3AM</td>
<td>0.687</td>
<td>0.0687</td>
</tr>
<tr>
<td>6AM</td>
<td>0.5089</td>
<td>0.1310</td>
</tr>
<tr>
<td>9AM</td>
<td>0.1567</td>
<td>0.4221</td>
</tr>
<tr>
<td>12PM</td>
<td>0.5089</td>
<td>0.1310</td>
</tr>
<tr>
<td>3PM</td>
<td>0.1567</td>
<td>0.4660</td>
</tr>
<tr>
<td>6PM</td>
<td>0.5089</td>
<td>0.1310</td>
</tr>
<tr>
<td>9PM</td>
<td>0.1567</td>
<td>0.4660</td>
</tr>
<tr>
<td>12AM</td>
<td>0.5089</td>
<td>0.1310</td>
</tr>
</tbody>
</table>

Table 4.4 Daily Energy Bill ($) for House A, B, and C for Frequency Day 1 and Day 2

<table>
<thead>
<tr>
<th></th>
<th>House A</th>
<th>House B</th>
<th>House C</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 Second TOU+Freq, f1</td>
<td>0.6837</td>
<td>0.0496</td>
<td>0.0687</td>
</tr>
<tr>
<td>60 Second TOU+Freq, f2</td>
<td>0.5089</td>
<td>0.1310</td>
<td>0.1567</td>
</tr>
<tr>
<td>5000 Second TOU+Freq, f1</td>
<td>1.0847</td>
<td>0.1835</td>
<td>0.1962</td>
</tr>
<tr>
<td>5000 Second TOU+Freq, f2</td>
<td>1.0924</td>
<td>0.4221</td>
<td>0.4660</td>
</tr>
</tbody>
</table>
The energy bills for the second frequency day are lower than the first for the houses under the 60 Second TOU+Freq rate. However, the energy bills for the 5000 Second TOU+Freq rate are more expensive for the second day although the maximum variation is only about $0.30. A more detailed study of the frequency variation for different days is presented in Chapter 5. The most noticeable result is that House A pays much more than the other houses under the 5000 Second TOU+Freq rate. This is because the 5000 second moving average price is much more expensive for frequency day 2 from 6 PM to 12 AM when House A uses most of its electricity. The 60 Second TOU+Freq rate
is better for equalizing the energy bills between houses.

4.5 Conclusion

As detailed in this chapter, a real-time, dynamic TOU+Freq rate benefits prosumers and encourages them to use ESS. Prosumers with load and PV save more by using an ESS under a real-time 60 second or 5000 second TOU+Freq hybrid rate than under a standard TOU rate. By responding to a real-time rate that reflects current supply and demand, prosumers will see more savings with energy storage and be incentivized to help balance the grid. The grid frequency provides a signal for energy imbalance and is an easy, autonomous way to construct a real-time price and provide ancillary services. Savings to their daily energy bill were achieved for houses with three different load patterns, considering their cost to ESS and variation in daily frequency. A bi-directional rate is the next step and will be designed and simulated in the next chapter.
CHAPTER

5

BI-DIRECTIONAL TOU AND FREQUENCY BASED HYBRID ELECTRICITY RATE

5.1 Problem Set-Up and Methods

For the bi-directional TOU and frequency based hybrid rate study, a 75% back-feeding tariff is included so that prosumers are incentivized to store excess PV generation and to balance their energy use locally before selling back to the grid. The frequency based pricing is added to the existing TOU rate, but with the 75% back-feeding tariff, prosumer’s consumption is billed at 100% of the rate and their generation is sold at 75% of the rate.

Similar data to Chapter 4 is used. PV and load data from three different homes in Austin, Texas, measured in May 2012 were used to formulate nine different PV and load profiles, courtesy of Pecan Street Inc. Dataport 2016. The cumulative trend of the loads provided matched the peak, mid-peak, and off-peak times of Hawaii Electric compared to other utility TOU schedules, so this rate was chosen as a baseline. Frequency data was obtained from Oak Ridge National Labs, CURENT, and University of Tennessee at Knoxville.

The sum of the nine load profiles is shown in Fig. 5.1, plotted with the Hawaii Electric TOU rate. The TOU rates used in Chapter 4, such as the TOU rate from Southern Edison and Duke Energy...
Progress did not have peak hours that corresponded with the peak times of the load profiles shown. Each of the nine load profiles are graphed separately later in this chapter.

![Figure 5.1 Sum of Nine Load Profiles and Hawaii TOU Rate](image)

Figure 5.1 Sum of Nine Load Profiles and Hawaii TOU Rate. For weekdays, Off-Peak: 9 PM to 7 AM, Mid-Peak: 7 AM to 5 PM, and Peak: 5 PM to 10 PM. Pecan Street Inc. Dataport 2016

Linear programming is used in this chapter as it was in Chapter 4, with a few minor changes. As in Chapter 4, it solves for a day-ahead schedule, or cumulative energy use, $P_{\text{grid}}(t)$, taking as inputs the electricity rate (TOU rate), PV and load forecast, and ESS initial state-of-charge (SOC), capacity, and power constraints. The total cost of energy to the prosumer should be minimized. The grid frequency is measured every one second and a moving average is calculated every one minute for the previous minute as designed for in Chapter 4. The ESS is sized as 10 kWh with a maximum charge and discharge of 4 kW, with an initial SOC as it’s lower bound at 0.2 and ESS charging and discharging efficiency of 0.999. The SOC upper bound of 0.9 is discussed more in the cost to ESS section as the bound settings are new in this chapter.

The linear programming problem is defined as $\min\{f^T x\}$. The decision variables are $x = [P_{\text{gridin}}(t), P_{\text{gridout}}(t), P_{\text{charge}}(t), P_{\text{discharge}}(t), \text{SOC}(t)]$. The total cost of energy to the prosumer
is minimized for one day with the objective function

$$\text{Min } f = \sum_{t=1}^{T} \tau C_{\text{grid}}(t)(P_{\text{gridin}}(t)-\gamma P_{\text{gridout}}(t))$$  \hspace{1cm} (5.1)$$

The power balancing equation is an equality constraint

$$P_{\text{gridin}}(t)-P_{\text{gridout}}(t) = P_{\text{load}}(t)-P_{\text{pv}}(t)+P_{\text{charge}}(t)-\eta P_{\text{discharge}}(t)$$  \hspace{1cm} (5.2)$$

followed by the ESS SOC calculation

$$SOC(t) = SOC_i + \frac{\tau}{\text{cap}} \sum_{j=1}^{t} (\eta P_{\text{charge}}(j)-P_{\text{discharge}}(j))$$  \hspace{1cm} (5.3)$$

In (1), \( t \) is the time in minutes (where \( T \) is 1440 minutes in one day), \( \tau \) is the time constant in hours, \( C_{\text{grid}}(t) \) is the cost of electricity (the electricity rate) in \$/kWh, \( \gamma \) is the back-feeding tariff, and \( P_{\text{gridin}}(t)-P_{\text{gridout}}(t) = P_{\text{grid}}(t) \) which is the power in kW flowing through the grid-connected meter. \( P_{\text{gridin}}(t) \) and \( P_{\text{gridout}}(t) \) must be positive. Equation (2) includes the load, \( P_{\text{load}}(t) \), PV generation, \( P_{\text{pv}}(t) \), charging power, \( P_{\text{charge}}(t) \) and discharging power \( P_{\text{discharge}}(t) \). The ESS charging and discharging efficiency is \( \eta \). In (3), \( SOC_i \) is the initial SOC (at \( t = 0 \)) and \( \text{cap} \) is the battery capacity in kWh.

The real-time price adjustment will be determined by the real-time frequency based price. Frequency based pricing reflects the balance of supply and demand on the grid and ultimately increases the value for ESS, which will be a mandatory, carbon neutral component to offset high uptake of PV and other renewable technologies. The real-time price will be calculated from the grid frequency and updated every one minute as described in Chapter 4 and in the following section of this chapter.

For prosumers with ESS, linear programming is used to make an energy schedule for the day-ahead TOU rate. Then the prosumer adjusts to their TOU schedule based on the real-time frequency based rate.

There are three models for the real-time price outcome used in this chapter:

1. **Linear Programming** to find the optimal possible energy bill, given that the frequency based price is known day-ahead and is combined with the TOU rate

2. **Response Curve** (Prosumer Response Method 1) to override the day-ahead schedule if the real-time price exceeds a price threshold
3. **Rule Based** (Prosumer Response Method 2) control which adds logic to the Response Curve to account for trends observed in the optimal bill from linear programming.

Linear Programming uses the TOU rate plus the frequency based rate as the input $C_{grid}(t)$, as a theoretical, but not realistic model. The Response Curve model is designed according to Fig. 5.2 which shows various curves for ESS frequency response to override the day-ahead schedule. The middle graph with the deadband from -0.2 $/kWh to 0.2 $/kWh consistently provided the lowest energy bill and is used as the Response Curve for the rest of this study. The Rule Based model adds rules to the Response Curve as will be shown in a later section.

![Real-time Response Curves](image)

**Figure 5.2** Real-time Response Curves

In this chapter, the TOU rate is referred to as such and is the baseline for comparisons to the TOU plus frequency based hybrid electricity rate. The TOU plus frequency based hybrid rate is referred to as TOU+Frequency or TOU+Freq for short in this chapter.

### 5.2 Frequency Based Rate Design

The objective for the frequency based rate design is to lower the energy bills of prosumers with ESS. Four different homes are considered using the load profile and the PV profile as depicted in Fig. 5.3. The load measures 33.0 kWh and the PV measures 20.9 kWh. Home A has Load, PV and ESS (L+PV+ESS), Home B has Load and ESS (L+ESS), Home C has Load and PV (L+PV), and Home D has only Load (L). The impact of the rate can be determined by studying the response of the four homes. If each home type is represented equally in a neighborhood, about half the homes will have...
PV, resulting in high uptake of DG, requiring frequency based pricing to incentivize prosumers to purchase ESS for secondary frequency support and to smooth imbalances between load and PV. As shown in Fig. 5.3, the load and PV generation are often unaligned as home owners leave for work during the day.

![Load and PV Profile used for Homes A, B, C, and D with the TOU rate. Pecan Street Inc. Dataport 2016](image)

The daily energy bills for Home A, B, C, and D have been calculated under the traditional TOU rate using linear programming below in Table 5.1. The home with load only, Home D pays $7.33. This home would save $3.91 just by installing PV to become Home C, paying $3.42. But if Home D added ESS, it would only save $0.56, becoming Home B with a bill of $6.77. Adding both PV and ESS increases the total savings by more than the sum of adding each individually (savings of $4.56 versus $4.47), as is seen with Home A paying $2.77.

The goal is to use frequency based pricing to add more incentives for ESS. Due to the misalignment of Load and PV profiles and the high uptake of PV, ESS is considered to be just as valuable as PV in this modern, distributed grid. Home A is consuming 33 kWh, but is producing 20.9 kWh of PV and contributing about 7 kWh of ESS, considering its defined upper and lower bounds, for a total of 27.9 kWh. For a net charge of 5.1 kWh, Home A should be paying closer to 15.5% of the total load cost (Home D) or $1.14. Or, if calculated according to PV savings, if $3.91 is saved by adding 20.9 kWh.
Table 5.1: Daily Energy Bill for Home A, B, C, and D using Linear Programming to Optimize for the TOU rate and TOU+Freq Rate ($)

<table>
<thead>
<tr>
<th></th>
<th>Home A (L+PV+ESS)</th>
<th>Home B (L+ESS)</th>
<th>Home C (L+PV)</th>
<th>Home D (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Energy Bill: TOU Rate ($)</td>
<td>2.77</td>
<td>6.77</td>
<td>3.42</td>
<td>7.33</td>
</tr>
<tr>
<td>Daily Energy Bill: TOU+Freq Rate ($)</td>
<td>1.01</td>
<td>5.22</td>
<td>3.38</td>
<td>7.42</td>
</tr>
</tbody>
</table>

kWh of PV, $0.187 worth of savings is fair for 1 kWh of value added, or $1.31 savings for 7 kWh of ESS. Savings of $1.31 would bring the desired bill of Home A to $2.11. This range will be referenced in designing the frequency based rate for Home A. The range for the other home with ESS, Home B, is $5.77 to $6.02.

A true cost/benefit analysis is the future work. However, this design aims to lower the energy bill for ESS to provide incentive for prosumers with PV and ESS to stay grid-connected versus off-grid and to represent energy flow going from prosumer to prosumer. As DERs grow, prosumer energy bills should decrease as they are providing their own generation. But as a reminder, the energy bill only considers the variable costs in this thesis. Prosumers may also pay a fixed fee each month to their grid authority.

5.2.1 Design Parameters

In real-time, the grid frequency is measured every one second and a moving average is calculated every one minute for the previous minute. To determine the frequency based price, a relationship between the moving average and price is designed as shown in Fig. 5.4 and detailed in Chapter 4 and Chapter 3. The design parameters are the slope K and the minimum and maximum price constraints. The daily bill is calculated for Home A and Home B in Fig. 5.5 by varying the slope K with a max/(-min) constraint of $0.05 and in Fig. 5.6 by varying the max/(-min) constraint with a constant slope of -4.

In this design, a slope K of -4 and a max/(-min) constraint of $0.05 were chosen so that the energy bill for Home A and Home B were $1.01 and $5.22, respectively for the combined TOU+Frequency rate (abbreviated as TOU+Freq) as shown in Table 5.1. These energy bills were calculated using linear programming, so the savings were designed to be higher than the range desired. Realistically, the prosumer will respond to the rate using the Response Curve or the Rule Based method because they will not be able to correctly predict the grid frequency for the day. The design accounted for these two methods by recognizing that all of the savings from linear programming are unlikely to be...
Figure 5.4 Price vs. Frequency

Figure 5.5 Bill for Slope K
Figure 5.6 Bill for Max/(-Min) Constraint

Figure 5.7 TOU and TOU+Freq Curves
This design achieves the desired goal of increasing the incentive for ESS to be equivalent to the savings from PV. The Hawaii Electric based TOU rate and the newly designed Hawaii TOU+Freq rate are presented in Fig. 5.7. The TOU+Freq rate ranges from 13 to 0.31 $/kWh, while the TOU rate has an off-peak of 0.18, a mid-peak of 0.23, and a peak of 0.26 $/kWh. A graph of the ESS SOC from Home A and Home B for each of the TOU and TOU+Freq Rates is shown in Fig. 5.8 to match the daily energy bills for the first two columns in Table 5.1. The SOC from the TOU+Freq rate follows the changes in the grid frequency for both Home A and Home B, with some variation due to the PV located at Home A.

![Figure 5.8 TOU and TOU+Freq SOC Results for Home A and Home B](image)

### 5.2.2 Variation in Daily Frequency

Using the designed TOU+Freq rate, the variation in prosumer behavior for five different days of grid frequency was tested. The energy bills for each of the five days are listed in Table 5.2 along with the TOU only bill for comparison. The average daily bill for Home A was $1.09 ± 0.07 and for Home B
Table 5.2 Daily Energy Bill ($) for Home A and B for five different days of frequency data

<table>
<thead>
<tr>
<th></th>
<th>Home A (L+PV+ESS)</th>
<th>Home B (L+ESS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOU</td>
<td>2.77</td>
<td>6.77</td>
</tr>
<tr>
<td>TOU+Freq Day 1</td>
<td>1.01</td>
<td>5.22</td>
</tr>
<tr>
<td>TOU+Freq Day 2</td>
<td>1.06</td>
<td>5.49</td>
</tr>
<tr>
<td>TOU+Freq Day 3</td>
<td>1.07</td>
<td>5.32</td>
</tr>
<tr>
<td>TOU+Freq Day 4</td>
<td>1.19</td>
<td>5.43</td>
</tr>
<tr>
<td>TOU+Freq Day 5</td>
<td>1.12</td>
<td>5.32</td>
</tr>
<tr>
<td>TOU+Freq Average</td>
<td>1.09 ± 0.07</td>
<td>5.36 ± 0.11</td>
</tr>
</tbody>
</table>

was $5.36 ± 0.11. Compared to the TOU rate, Home A lowered its bill by $1.68 and Home B lowered its bill by $1.41. Home A had greater savings because it had the additional opportunity to save money by storing PV.

The variation in daily frequency can be seen in the plots of the ESS SOC curves were for each of the homes, with Home A in Fig. 5.9 and Home B in Fig. 5.10. The TOU+Freq SOC were determined using linear programming. There is slightly more SOC variation for Home A due to the presence of PV which can recharge the ESS after it is discharged for frequency support.

Compared to the variation between Home A and Home B for the same day of measured frequency (Fig. 5.11), there is more variation for one home (Home A in Fig. 5.12) with different frequency days. This is to be expected as the frequency component makes up a large portion of the TOU+Freq rate. The TOU+Freq rate adds $±0.05 to the TOU rate, giving it a total range of $0.10 while the TOU rate has a range of $0.08 between its peak and off-peak price. The difference in the SOC response for Home A and Home B is the inclusion of the PV profile for Home A.

5.3 Cost to Energy Storage System (ESS)

To account for use of the battery ESS, a cost function for the battery was developed to accurately represent aging of the ESS. For ESS that cycle very slowly (less than 1C or one cycle per hour) and do not engage in deep depths of discharge (DOD), the primary means of degradation result from temperature of the system and average SOC [Sm12][La13][Du16]. The calendar life of the battery is determined by the degradation rate, which can be determined by the resistance growth rate and the capacity fade rate as shown in Fig. 5.13 below.
Figure 5.9 Home A (L+PV+ESS) SOC Results for Variation in Daily Frequency

Figure 5.10 Home B (L+ESS) SOC Results for Variation in Daily Frequency
Figure 5.11 SOC Frequency Day 1 for Home A and B

Figure 5.12 SOC Frequency Day 1 and 2 for Home A
At less than 0.4 SOC, fade rates are relatively insensitive to temperature, but they are strongly sensitive to temperature at greater than 0.8 SOC \[\text{Smi12}\]. For this reason, the minimum and maximum SOC are limited to 0.2 and 0.9, respectively \[\text{Du16}\]. The battery end of life is met when it has reached 20% cyclable lithium capacity loss, as shown by the horizontal "x" lines defined as the number of years until end of life in Fig. 5.13.

To determine the cost to the ESS for one day from its average SOC, the relationship of the average SOC to the capacity fade rate is determined from Fig. 5.13. Five data points measuring the capacity fade at 26 degrees Celsius from each SOC line were used to determine a relationship

\[
CF = -(1.042e^{-11})S^4 - (6.25e^{-10})S^3 - (7.083e^{-8})S^2 - (7.75e^{-6})S - 0.00151
\]  

(5.4)

where \(CF\) is the capacity fade rate and \(S\) is the average SOC. From the capacity fade rate, three data
where $L$ is the lifetime in years. To calculate the ESS cost per day, the total cost of the ESS ($3500 for 10 kWh quoted by Tesla [Tes]) can be divided by the lifetime in days. An accurate SOC calculation is assumed based on ESS charging and discharging power. In the literature, the current and voltage of the ESS produce a more accurate SOC [Du16].

The daily average SOC and calculated ESS cost are shown for Home A and Home B for the variation in daily frequency in Table 5.3 below.

As was seen in Fig. 5.8, Home A has a much lower average SOC, and therefore cost to ESS than Home B for the TOU baseline rate. This is due to Home B consisting of only load and ESS. Under the TOU rate, Home B charges during off-peak hours in the morning and maintains maximum SOC during the middle of the day before discharging during peak hours. Therefore, in comparison to the TOU+Freq results, Home B has a much lower average SOC and ESS Cost under the TOU+Frequency based rate. Home A has a slightly increased ESS cost for the TOU+Freq rate, as it’s SOC under the TOU rate climbs sharply to reach a maximum SOC for a brief period before the peak pricing starts. During the TOU+Freq rate, the SOC has incentive to charge earlier in the day and not necessarily in accordance with PV generation. According to the Table, the average SOC for the TOU+Freq has increased 45% from the TOU SOC for Home A, averaging at 0.62 ± 0.02. It’s cost to ESS has increased

### Table 5.3 Daily Average SOC (out of 1) and ESS Cost ($) for Home A and B for five different days of frequency data

<table>
<thead>
<tr>
<th></th>
<th>Home A (L+PV+ESS)</th>
<th>Home B (L+ESS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg SOC</td>
<td>ESS Cost ($)</td>
</tr>
<tr>
<td>TOU</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>TOU+Freq Day 1</td>
<td>0.62</td>
<td>0.58</td>
</tr>
<tr>
<td>TOU+Freq Day 2</td>
<td>0.63</td>
<td>0.60</td>
</tr>
<tr>
<td>TOU+Freq Day 3</td>
<td>0.64</td>
<td>0.60</td>
</tr>
<tr>
<td>TOU+Freq Day 4</td>
<td>0.64</td>
<td>0.61</td>
</tr>
<tr>
<td>TOU+Freq Day 5</td>
<td>0.58</td>
<td>0.54</td>
</tr>
<tr>
<td>TOU+Freq Average</td>
<td>0.62 ± 0.02</td>
<td>0.59 ± 0.03</td>
</tr>
</tbody>
</table>
36 % from the TOU rate ESS cost, averaging at $ 0.59 ± 0.03. For Home B, the average SOC for the TOU+Freq rate has decreased 2 % from the TOU SOC averaging at 0.64 ± 0.02. It's cost to ESS has decreased 3 % from the TOU rate ESS cost, averaging $ 0.60 ± 0.02.

5.4 Rule Based Prosumer Response Method

The Rule Based prosumer response method for real-time response to the TOU+Freq rate was the final method for anticipating the ESS behavior and Energy Bills of Home A and Home B. This method aims to build upon the Response Curve Method (shown in the beginning of this chapter in Fig. 5.2 in order to gain the prosumer a lower daily energy bill. The Response Curve prosumer method determines the strategic ESS charge or discharge value according to the frequency-based price component of the TOU+Freq rate. The strategic ESS charge or discharge value is then substituted for the day-ahead schedule for the ESS determined by the TOU component of the TOU+Freq rate. By graphing the optimal prosumer response SOC using Linear Programming next to the Response Curve SOC results, rules can be developed to move the Response Curve SOC closer to the Linear Programming SOC. The Linear Programming SOC is the idealistic solution, assuming that the grid frequency can be perfectly predicted at the start of the day. The TOU SOC curve is the baseline curve the Response Curve and Rule Based methods adjust to achieve maximum savings under the TOU+Freq rate.

The SOC curves for Home A and Home B for each of the five different days of frequency data are included below for study. The Rule Based prosumer response method developed is explained in Table 5.4. From studying the SOC curves adjustments were made to achieve SOC targets depending on the time of day. These rules adjusted the Response Curve method. For example, during the mid-peak, the Response Curve method was resulting in ESS that were discharging for Home B before the expensive peak period was reached. A rule was added to prevent discharging if the SOC < 0.7 during this period.

The SOC for Frequency Day 1 is graphed for Home A (Fig. 5.14) and Home B (Fig. 5.15). The SOC for Frequency Day 2 is graphed for Home A (Fig. 5.16) and Home B (Fig. 5.17). The SOC for Frequency Day 3 is graphed for Home A (Fig. 5.18) and Home B (Fig. 5.19). The SOC for Frequency Day 4 is graphed for Home A (Fig. 5.20) and Home B (Fig. 5.21). The SOC for Frequency Day 5 is graphed for Home A (Fig. 5.22) and Home B (Fig. 5.23). The legend in the first two figures applies to the rest of the graphs in this group (LP is Linear Programming).

The daily average energy bill for the TOU rate and TOU+Freq rate comparing Linear Programming, the Response Curve method, and the Rule Based Method for Home A and Home B is shown in Table 5.5. The ESS Cost and ESS Cost % Change are included as well. It can be observed that the
Rule Based method is able to improve upon the Response Curve method to lower the Energy Bill closer to the Linear Programming result. All three methods improve upon the TOU rate bill. Under the TOU+Freq rate Home A and Home B are incentivized to buy ESS and lower their bill using the Rule Based method. The Response Curve method is less likely to be used as it produces higher bills for both homes. The ESS Cost is lower for the Response Curve, but the difference is small. For Home A, for example, the ESS Cost is $0.15 more expensive for the Rule Based method compared to the Response Curve method. However, the energy bill for the Rule Based method is $0.44 cheaper,

![Image](image1.png)

**Figure 5.14** Home A SOC Frequency Day 1

![Image](image2.png)

**Figure 5.15** Home B SOC Frequency Day 1
**Figure 5.16** Home A SOC Frequency Day 2

**Figure 5.17** Home B SOC Frequency Day 2
**Figure 5.18** Home A SOC Frequency Day 3

**Figure 5.19** Home B SOC Frequency Day 3
Figure 5.20 Home A SOC Frequency Day 4

Figure 5.21 Home B SOC Frequency Day 4
**Figure 5.22** Home A SOC Frequency Day 5

**Figure 5.23** Home B SOC Frequency Day 5
Table 5.4 Rule Based Prosumer Response Method, according to $t =$ time in minutes

<table>
<thead>
<tr>
<th>If $t &lt; 173$ (off-peak)</th>
<th>No changes to Response Curve Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>If $316 &lt; t \leq 173$ (middle of off-peak)</td>
<td>Do not discharge if $SOC &lt; 0.5$</td>
</tr>
<tr>
<td>If $420 &lt; t \leq 316$ (end of off-peak)</td>
<td>Do not discharge</td>
</tr>
<tr>
<td>If $920 &lt; t \leq 420$ (mid-peak)</td>
<td>Do not discharge if $SOC &lt; 0.7$</td>
</tr>
<tr>
<td>If $1020 &lt; t \leq 920$ (end of mid-peak)</td>
<td>Do not discharge</td>
</tr>
<tr>
<td>If $1320 &lt; t \leq 1020$ (peak)</td>
<td>No changes to Response Curve Method</td>
</tr>
<tr>
<td>If $t &gt; 1320$ (off-peak)</td>
<td>Do not charge if $SOC &gt; 0.25$</td>
</tr>
</tbody>
</table>

negating the extra cost to ESS. As discussed in the previous section, the ESS cost is more expensive for the TOU+Freq rate for Home A, but less expensive for Home B compared to the TOU rate. The final daily average Rule Based energy bill falls within the desired range for Home A ($1.14$ to $2.11$) and Home B ($5.77$ to $6.02$), calculated at the beginning of this chapter.

Table 5.5 Daily Average Energy Bill and ESS Cost ($) for Home A and B for five different days of frequency data using linear programming and two prosumer response methods

<table>
<thead>
<tr>
<th>TOU Bill ($), ESS Cost ($)</th>
<th>Home A (L+PV+ESS)</th>
<th>Home B (L+ESS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOU+Freq</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Programming</td>
<td>Linear Programming</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>Response Curve</td>
<td>Response Curve</td>
<td>Response Curve</td>
</tr>
<tr>
<td>Rule Based</td>
<td>Rule Based</td>
<td>Rule Based</td>
</tr>
<tr>
<td>Energy Bill ($)</td>
<td>1.09</td>
<td>5.36</td>
</tr>
<tr>
<td>ESS Cost ($)</td>
<td>0.58</td>
<td>0.60</td>
</tr>
<tr>
<td>ESS Cost % Change</td>
<td>42 %</td>
<td>-6%</td>
</tr>
</tbody>
</table>

82
### 5.5 Daily Average Energy Bill for Home A, B, C, and D

In conclusion, the daily average energy bill for each of the four homes is displayed in Table 5.6. In the previous sections, the focus was only on Home A and Home B which both have ESS. However, Home C and Home D are included in the analysis here in order to compare the outcome for homes with Load and PV and just Load. Demand response is not considered for Home C and Home D, so their energy bills are the same in the second to fourth rows because they are charged according to the TOU+Freq rate but are not responding to it or any dynamic pricing mechanism. For the five different days of frequency data, Home C pays $0.05 less and Home D pays $0.13 more per day. Both of these differences are fairly negligible, but homes that only have load like Home D could be exempt from the TOU+Freq rate and pay according to a flat rate, for example. The primary outcome of the TOU+Freq rate is that it lowers energy bills for Home A and Home B while providing frequency support to the grid authority.

#### Table 5.6 Daily Average Energy Bill ($) for Home A, B, C, and D, Comparing TOU Rate to TOU+Freq Rate for five different days of frequency data

<table>
<thead>
<tr>
<th></th>
<th>Home A (L+PV+ESS)</th>
<th>Home B (L+ESS)</th>
<th>Home C (L+PV)</th>
<th>Home D (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOU</td>
<td>2.77</td>
<td>6.77</td>
<td>3.42</td>
<td>7.33</td>
</tr>
<tr>
<td>TOU+Freq Linear Programming</td>
<td>1.09</td>
<td>5.36</td>
<td>3.37</td>
<td>7.46</td>
</tr>
<tr>
<td>TOU+Freq Response Curve</td>
<td>2.18</td>
<td>6.48</td>
<td>3.37</td>
<td>7.46</td>
</tr>
<tr>
<td>TOU+Freq Rule Based</td>
<td>1.74</td>
<td>5.95</td>
<td>3.37</td>
<td>7.46</td>
</tr>
</tbody>
</table>

### 5.6 Thirty-two Home Study

In this section, a neighborhood scenario is studied to observe the impact of multiple homes like Home A, B, C, and D previously. Eight individual homes are assigned to each group, now labeled Group A (L+PV+ESS), Group B (L+ESS), Group C (L+PV), and Group D (L). For sake of comparison,
the same eight homes are assigned to each group. These homes have various load and PV profiles (nine in each category) provided by Pecan Street Inc. Dataport 2016 and mentioned in the beginning of this chapter. The nine load profiles are shown below in Fig. 5.24. The nine PV profiles are shown in Fig. 5.25. The eight homes defined for each group are shown in Table 5.7. All eight homes have a load and PV profile, but the PV profile is neglected for Groups B and D who do not have PV.

![Load Profiles](image)

**Figure 5.24** Nine Load Profiles from Pecan Street Inc. Dataport 2016.

The SOC graphs for Group A and Group B, which have ESS are shown below for the TOU and TOU+Freq rate for one day of frequency data. The eight homes in each group are labeled h1-h8 and represent the same colors on each graph. The first two graphs show the ESS SOC for Group A (Fig. 5.26) and Group B (Fig. 5.27) Home 1 (h1) has the same Load and PV curve used earlier in the chapter for Home A, B, C, and D. However, it’s SOC curve looks slightly different in these two graphs because the efficiency constant was not introduced in the linear programming model and the SOC for Group B does not stay at 0.9 SOC during the mid-peak period as it should. (It's inefficient to
Figure 5.25 Nine PV Profiles from Pecan Street Inc. Dataport 2016.

Table 5.7 Eight Homes Defined for Each Group in the Thirty-Two Home Study

<table>
<thead>
<tr>
<th>Home (h)</th>
<th>Load Profile (L) Solar Profile (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>h1</td>
<td>4L 3P</td>
</tr>
<tr>
<td>h2</td>
<td>7L 2P</td>
</tr>
<tr>
<td>h3</td>
<td>9L 7P</td>
</tr>
<tr>
<td>h4</td>
<td>3L 8P</td>
</tr>
<tr>
<td>h5</td>
<td>2L 5P</td>
</tr>
<tr>
<td>h6</td>
<td>5L 8P</td>
</tr>
<tr>
<td>h7</td>
<td>8L 5P</td>
</tr>
<tr>
<td>h8</td>
<td>6L 1P</td>
</tr>
</tbody>
</table>
discharge and then charge during the mid-peak for a home with only Load and ESS).

The following graphs depict Group A and Group B for each of the three prosumer response models for the TOU+Freq rate. In this case, the rate constraints were chosen differently than in the case earlier in the chapter. The slope $k$ is -8 and the max/(-min) constraint is $0.18$. This results in more aggressive savings for the prosumers with ESS as shown later in Table 5.8. Fig. 5.28 shows the linear programming model for the TOU+Freq rate for Group A and Fig. 5.29 shows the same results for Group B. During the start of the peak period at 5 PM, Group A generally has a higher SOC because it can use excess PV generation to stay charged. The SOC from the Response Curve method is shown for Group A in Fig. 5.30 and for Group B in Fig. 5.31. There is much more variation between the eight homes in the SOC for Group A. The same trend applies to the SOC from the Rule Based method shown for Group A in Fig. 5.32 and Group B in Fig. 5.33.

![Figure 5.26 Group A SOC TOU](image-url)

**Figure 5.26** Group A SOC TOU
Figure 5.27 Group B SOC TOU

Figure 5.28 Group A SOC Linear Programming
Figure 5.29 Group B SOC Linear Programming

Figure 5.30 Group A SOC Response Curve
Figure 5.31 Group B SOC Response Curve

Figure 5.32 Group A SOC Rule Based
Figure 5.33 Group B SOC Rule Based

Table 5.8 gives a summary of the daily energy bill and ESS cost for Group A and Group B for all of the scenarios included in the graphs plotted for this section. The results reflect the outcome earlier in this chapter for Home A and Home B. Both groups are incentivized with more savings under the TOU+Freq rate than the TOU rate when they have ESS. The TOU+Freq rate resulted in more savings in this section as a reflection of the parameters chosen to design the rate. Because of this, Group A has a negative energy bill, meaning that these homes would make a profit. Additionally the Rule Based method has about the same outcome as the Response Curve, with a slightly more expensive cost to ESS for the Rule Based method. This table only reflects the daily energy bill from the frequency data day 1.

Table 5.9 summarizes the energy bills for all four groups for one day of frequency data. The TOU rate is compared to the most likely response method for the TOU+Freq rate: the Response Curve method (which slightly over performed the Rule Based method shown in Table 5.8). As shown, Group C has a $0.05 higher energy bill for the TOU+Freq rate and Group D has a $0.35 higher energy bill. Group A and Group B both save money with their ESS.
Table 5.8 Daily Energy Bill and ESS Cost ($) for Group A and B using linear programming and two prosumer response methods for Frequency Day 1

<table>
<thead>
<tr>
<th>TOU Bill ($), ESS Cost ($)</th>
<th>Group A (L+PV+ESS)</th>
<th>Group B (L+ESS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.13, 0.45</td>
<td>5.79, 0.58</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOU+Freq</th>
<th>Linear Programming</th>
<th>Response Curve</th>
<th>Rule Based</th>
<th>Linear Programming</th>
<th>Response Curve</th>
<th>Rule Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Bill ($)</td>
<td>-3.28</td>
<td>-2.00</td>
<td>-1.93</td>
<td>0.39</td>
<td>1.76</td>
<td>1.76</td>
</tr>
<tr>
<td>ESS Cost ($)</td>
<td>0.56</td>
<td>0.53</td>
<td>0.61</td>
<td>0.54</td>
<td>0.51</td>
<td>0.57</td>
</tr>
<tr>
<td>ESS Cost % Change</td>
<td>26 %</td>
<td>18%</td>
<td>36 %</td>
<td>-7 %</td>
<td>-13 %</td>
<td>-3 %</td>
</tr>
</tbody>
</table>

Table 5.9 Daily Energy Bill ($) for 32 Home Study Comparing TOU Rate to TOU+Freq Rate using the Response Curve method for Frequency Day 1

<table>
<thead>
<tr>
<th>Daily Energy Bill: TOU rate ($)</th>
<th>Group A (L+PV+ESS)</th>
<th>Group B (L+ESS)</th>
<th>Group C (L+PV)</th>
<th>Group D (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.13</td>
<td>5.79</td>
<td>2.84</td>
<td>6.34</td>
</tr>
<tr>
<td>Daily Energy Bill: TOU+Freq rate ($)</td>
<td>-2.00</td>
<td>1.76</td>
<td>2.89</td>
<td>6.69</td>
</tr>
</tbody>
</table>

5.7 Conclusion

This chapter simulated a bi-directional TOU and real-time frequency based electricity rate for prosumers. The rate was designed so that prosumers could save just as much as they would per kWh for PV generation under a net-metered TOU rate with a 75% tariff for reverse power flow. Linear programming was used to solve for the day-ahead schedule and three methods were compared to simulate the prosumer’s response to the real-time price component. The variation in daily frequency was studied for five different days of frequency data to find that the energy bill only varied ± $0.07 per day for Home A and ± $0.11 for Home B. The cost to the ESS was calculated according to the calendar life measured by the average SOC for each day. The Rule Based method for prosumer response provided a realistic strategy to lower the prosumer’s bill to the specified design goals. The daily average energy bill for a home with load, PV, and ESS decreased from $2.77 to $1.74. The
daily average energy bill for a home with load and PV decreased from $6.77 to $5.95. A thirty-two home study compared the SOC curves and energy bills for homes with different load and PV curves. Homes with PV and ESS can lower their energy bill the most.

As uptake of renewable DG grows, energy storage will be needed to maintain the load and net power consumption will contribute to the duck curve as well as cause frequency deviations. To solve this problem, prosumers must be disincentivized to inject their excess generation onto the grid, as was shown in this chapter. Similar to the energy markets of ISOs, this work proposes that prosumers respond to dynamic markets by planning a day-ahead schedule for known energy transactions, such as the TOU rate, and a real-time adjustment for grid balancing, via a real-time price. The bi-directional frequency based rates developed in this chapter resulted in prosumers charging and discharging to follow the grid frequency.
6.1 Conclusion

In this thesis a frequency based real-time price was designed and simulated for a residential prosumer.

First, the introduction detailed background on grid ancillary services and DERs. Frequency control in the electric grid was explained as well as ancillary services providing frequency support. The U.S. grid is evolving towards deregulation, DSOs, dynamic pricing, and transactive energy. As a control mechanism for energy management, transactive control is the highest layer of microgrid control. As the move towards deregulation continues, The Energy Internet may rule the future smart grid, providing a lateral network of connected devices who can buy and sell energy anywhere to anyone through prosumer-to-prosumer transactions.

Chapter 2 introduced the concept of prosumers and a dynamic frequency, based price. A price-reactive scheme was based off the grid frequency and simulated for a prosumer. The prosumer’s response was optimized and energy bill calculated. These results formed the basis from which to develop the hybrid TOU and frequency based rates in Chapter 4 and 5. The benefits of prosumers providing ancillary services was discussed.

Chapter 3 discussed the market structure, energy management framework, and enabling technol-
ogy for prosumers in the future grid, as building blocks for dynamic, transactive, and also frequency based real-time pricing. The energy market for prosumers will be similar to the existing market at the ISO level. Day-ahead or hour ahead energy scheduling will occur, followed by real-time pricing to adjust to changes in the scheduled price. The SST will provide frequency measurement, isolation, voltage and power control between the prosumer and the grid. As an energy router, the SST can control power flow to and from a prosumer and its devices. An experimental demonstration of the energy routing capability was shown.

Chapter 4 designed and simulated a single direction TOU and frequency based real-time rate. The rate was defined by a baseline TOU price added to the dynamic frequency based real-time price. A linear programming model was used to determine how the prosumer will optimize it's ESS. The energy bill was calculated for one day for multiple rate types. The frequency based hybrid rates provided the most savings to the prosumer, lowering their daily energy bills to near zero while providing frequency support to the grid. Variations among prosumer load curves were compared in the analysis of the their daily energy bill.

Chapter 5 defined the design parameters for a bi-directional TOU and frequency based real-time hybrid electricity rate to achieve lower daily energy bills for prosumers with energy storage. The savings prosumers with PV saw under a net-metered TOU rate were replicated for prosumers with ESS using the frequency based rate. Prosumers in the simulation calculated a day-ahead energy schedule and used one of three methods for the real-time adjustment according to the energy management framework proposed in Chapter 3. The cost to ESS was calculated based on the average SOC, variation in frequency was considered, and the outcome for multiple homes with different load and PV curves was studied. In the end, prosumers with ESS charged and discharged according to the grid frequency to lower their bill and provide frequency support. ESS was also used to store excess solar during periods of low profit, corresponding to supply saturation on the grid. A 60 second frequency moving average was recommended, with a slope K of -4 and a max/(−min) constraint of $0.05. The Rule Based Prosumer Response Method yielded the most realistic results and achieved the desired energy savings for prosumers with ESS based on an equivalent value of ESS to PV by $/kWh or savings per kWh.

6.2 Future Work

In this thesis, only the variable costs of electricity are taken into account. This was done within the framework of moving to a zero marginal cost society and an economy where distributed generation and energy storage are affordable and easy to purchase and install. Dynamic and frequency based pricing should be added to a comprehensive cost/benefit analysis to determine the overall benefits
and barriers to distributed, decentralized grids. The majority of utility costs are fixed, so the proportion of the energy bill that is based on prosumer consumption is not necessarily representative of the variable costs to the utility. Every utility, grid balancing authority, and geographic location is different. A location specific rate study is needed to determine fair profits to the utility under the rate structure proposed in this thesis. If prosumers generate more of their own electricity, they should pay less. Through transactive energy they will be basically buying and selling to each other. However, a fair, fixed, monthly charge is likely necessary to compensate for grid infrastructure and other utility costs. As the grid modernizes, the parameters and components of energy and electricity costs will change. Additional research is needed to study these changes, needs, and soft costs.

Second, a simulation for an islanded neighborhood AC microgrid is needed to study the measurable impact of the frequency based rate on the grid frequency and stability. Such an AC microgrid should consist of a group of homes with high uptake of rooftop PV or DG. Ideally DG should represent around 50% of the total generation with conventional or traditional generation filling in the gap. In this case DG and ESS will work side by side with conventional governor control and AGC to maintain grid frequency. Most research defines frequency deviations by disturbances by a load drop or generator gone offline. However, the frequency impact of small loads changing in an islanded microgrid is necessary to determine the affect of dynamic and frequency based pricing on smaller, secondary frequency deviations. From such a simulation, the required dynamic cost of electricity can be determined to stabilize the microgrid. And, strategies and operational rules can be designed to conduct a decentralized grid of devices so that frequency is safely maintained at equilibrium.

Additionally, voltage could also be explored as a pricing mechanism or component. Similar to frequency, the grid voltage must be maintained within a safe range and fluctuates according to energy consumption of devices. Over voltage issues occur if too much distributed generation or PV power penetrates a line. Reactive power also plays a role. Pricing mechanisms could incentivize prosumers and nodes to work together to maintain the grid voltage.

Lastly, locational marginal pricing is a key factor to managing grid energy flow and could be used as price-reactive control. A long term and seasonal study of real-time frequency based pricing should also be included. Uncertainty in the predicted load and PV curves should be taken into account. And, the role of the DSO and control architecture for energy pricing in decentralized grids, IOT, and the Energy Internet will be continued research areas.
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